PHYSICS

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PHYSICS

FOR

STUDENTS OF MEDICINE

BY

ALFRED DANIELL, M.A., LL.B., D.Sc., F.R.S.E.,

ADVOCATE AND BARRISTER-AT-LAW; EXAMINER IN PHYSICS TO
THE ROYAL COLLEGE OF PHYSICIANS OF EDINBURGH; FORMERLY LECTURER ON
PHYSICS IN THE SCHOOL OF MEDICINE, EDINBURGH; AUTHOR OF
'A TEXT-BOOK OF THE PRINCIPLES OF PHYSICS.'

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MACMILLAN AND CO., Ltd.
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PREFACE

Until within a recent period the Student of Medicine was launched into his professional studies and floated onwards towards his professional degree or qualifications without his receiving, so far as the regulations of the General Medical Council were concerned, any explicit direction that he must of necessity turn his attention to the subject of Physics. The consequence of this was that he mostly came unprepared to the consideration of matters involving in many cases the application of physical principles; and this he did to the embarrassment both of himself and of his teachers.

During the continuance of this state of things much was said as to the absolute necessity of a knowledge of Physics on the part of the Student of Medicine; and considerable discussion was evoked. In this I took some part; and I did some pioneering work between 1878 and 1883 by delivering courses of lectures in the School of Medicine, Edinburgh, on "Medical Physics."

Since then it has been gratifying to find that, under their new regulations which came into force in 1892, the General Medical Council ordained that the study of Physics was thenceforward to form part of the extended course of professional study.

Under the new order of things, it was suggested to me, by members of the medical profession to whose opinion I felt bound to defer, that I might render a service if I prepared a smaller book on Physics for the use of Students of Medicine; and I have had great pleasure in acting upon this suggestion as opportunity offered.

The following pages are not a mere abstract of my larger work on the *Principles of Physics* (London: Macmillan). There must naturally be considerable parallelisms: but there are also considerable divergences in the mode of treatment; and some portions of this small book are even fuller than the corresponding portions of the larger.

This little volume is obviously not intended to be exhaustive; from its size there must inevitably be omissions: but I trust that none of these are such as to interfere seriously with its usefulness. Again, since the book is intended for a special class of students, the subjects which most closely concern them will be found treated in greater detail than those which are of less direct utility. On the other hand, it is to be noted that this volume does not profess to discuss moot points in the application of physical principles to medical science, or to anticipate any practical directions as to methods of treatment or the like: the proper time for the discussion of such topics is reached in subsequent stages of the curriculum, when a general preparatory course of Physics has already been gone through.

Further, this work is not designed in any way to supersede but rather to clear the ground for practical teaching and demonstration. The Student of Medicine is something like a Student of Engineering, and his knowledge of Physics ought above all things to be real and actual. He ought to become personally acquainted with each piece of apparatus, and to satisfy himself as to how it works; and he ought to see phenomena for himself. No book, and no mere lectures, can supply this practical knowledge; and on this ground I venture to think that the subject of Physics, looked at from a medical point of view, ought in every case to form an experimental part of the professional curriculum.

I trust that this book may be found to combine two main functions; that of giving the Student of Medicine a broad general view of Elementary Physics as a whole, and that of providing a satisfactory course of preparatory matter, which shall prove interesting to him and put him in a position better to understand the specialised instruction which he will receive during the later stages of his study.

I shall be grateful for any suggestions which may tend to increase the utility of the book, to cure any defects, or to remove any blemishes from it.

ALFRED DANIELL.

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Page 2, l. 10 from foot: One sq. cm. = 0·1550 sq. in. = 0·0010764 sq. ft.
One sq. ft. = 929·014 sq. cm.
One cub. cm. = 0·0610254 cub. in.
One litre = 1·7607 British pint.

Page 4, l. 17 from foot: One British gallon = 4·5436 litres.
,, ,, pint = 0·56795 or nearly 0·568 litre.
One fluid ounce = 28·4 cub. cm.

CHAPTER I

UNITS OF MEASUREMENT

SCIENTIFIC men use the **centimetre**, the **second**, and the **gramme** as their **units** of length, time, and mass; and by adhering to this—or indeed by adhering to any system of units, such as the Foot, the Second, and the Pound, or the foot, the minute, and the grain, so long as all measurements are effected in terms of the same fundamental units—a great advantage is secured, namely, that when a problem is solved by means of a known mathematical equation which sets forth the law of the phenomenon in question, the answer comes out in terms of the same system of units, and needs no farther reduction. Physical quantities measured in terms of the Centimetre, the Gramme, and the Second, are said to be measured in units of the **C.G.S. system**, or in **C.G.S. units.** We shall, in the main, adhere to this; for the student will find it a labour-saving device to stand steadfastly by one system.

The Position of a point on a Line may be stated in terms of its distance, along the line, from a starting-point agreed upon. That of a point on a Surface may be stated by a method analogous to the statement of the Latitude and Longitude of a place on the earth's surface; and thus we may have the "log" of any particular object in a microscopical preparation, which may be found again at any time if we record the amount by which the stage must be shifted forward, and to one side, when the slide is put upon it in a definite position. The position of a point in Space may be specified in an analogous way by stating its height and its distance in horizontal and lateral directions; and on this principle it has been found possible to devise apparatus for recording the outline of statuary, etc., or even for mechanically reproducing these.

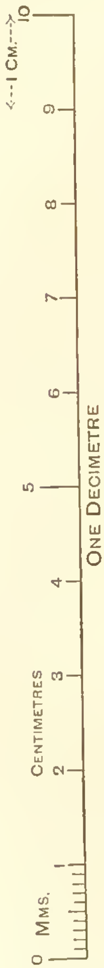


Fig. 1.

The **unit of length** usually employed in physical work is the **Centimetre.**

One **centimetre** (cm.) = 0·3937 inch = $\frac{1}{10}$ decimetre = $\frac{1}{100}$ metre.

One decimetre = 10 cm. = $\frac{1}{10}$ metre.

One metre = 100 centimetres = 1000 millimetres = 3·28087 feet = 3 ft. $3\frac{3}{8}''$ *less* $\frac{1}{219}$ inch.

One millimetre (mm.) = $\frac{1}{10}$ cm. = $\frac{1}{25 \cdot 4}$ inch.

One micron (μ) = $\frac{1}{1000}$ millimetre (Royal Microscop. Soc.'s standard) = 0·0001 cm. The same symbol μ is also applied to 0·000000,1 cm., as where it is said that the wave-length of a particular kind of light is 600 μ, or 0·00006 cm.

One "tenth-metre" = 1 metre ÷ 10^{10} = 0·000,000,01 cm.

One inch = 25·4 mm. = 2·54 cm.; one foot = 30·48 cm.

An English half-penny is 1 inch in diameter; a penny 1·2 inch; a French sou (5 centimes) is $2\frac{1}{2}$, a two-sous (10 c.) 3 centimetres in diameter.

One kilometre = 1000 metres = 100,000 cm. = 0·621377 mile.

One mile = 1·6093 kilometres.

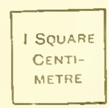


Fig. 2.

One **square cm.** = 0·1496 sq. inch = 0·0010417 sq. ft.

One sq. inch = 6·4516 sq. cm.; one sq. ft. = 929·0304 sq. cm.

One **cubic cm.** = 0·0610325 cub. inch = 0·00035317 cub. ft.

One cub. inch = 16·386 cub. cm.

One cub. ft. = 28,315 cub. cm. = 28·315 litre = 0·028315 cub. metre.

One cubic decimetre = one **Litre** = 1000 cub. cm. = $\frac{1}{1000}$ cub. metre = 0·035317 cub. ft. = 1·7657 British pint.

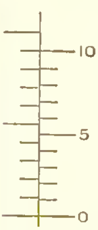
One cubic metre = 1000 cub. decimetre = 1,000,000 cub. cm. = 1000 litres = 35·317 cub. ft. = 61025·386 cub. inches.

In careful measurement a **Vernier** has often to be employed, in addition to the measuring scale made use of. Verniers are small subsidiary scales which may be slipped up and down the main scale. In the **Barometer-Vernier** (Fig. 3), ten divisions on the vernier are equal to eleven on the main scale; and the numbers on the vernier run back, against the numbers on the main scale. Suppose we have to find the height of the mercury in the barometer, and that it stands somewhere between 29·5 and 29·6 on the main scale. We slip the vernier down until its **zero** coincides as exactly as possible with the top of the mercury; then we look **down** the vernier until we find the vernier mark coinciding with a graduation mark of the main scale. Say that the vernier mark 6 does this (coinciding with 28·9 on the main scale), then the missing number is 6, and the reading of the instrument is 29·56.

SCALE: VERNIER (BAROMETER)

Fig. 3.

In the **Sextant-Vernier**, largely used in instruments of Continental make, ten divisions on the vernier are equal to nine on the main scale; and the numbers on the vernier run in the same direction as those on the main scale (Fig. 4). Again the **zero** of the vernier is laid opposite the level of the mercury, and the mark **up** the scale which first coincides with a graduation mark of the main scale gives the number required in the second place of decimals.



SCALE: VERNIER (SEXTANT)

Fig. 4.

In all cases of measurement care must be taken that the eye looks directly, **not obliquely**, at both the object and the scale. If this is neglected errors are induced through **parallax**, or apparent mutual displacement of the object and the scale.

The **least visible** white granule on black paper seems to be about $\frac{1}{2000}$ inch, or $\frac{1}{80}$ mm., in diameter, not quite twice the greatest diameter of a red blood corpuscle.

In Nobert's latest test-plates for microscopic lenses, the finest graduation consists of parallel lines ruled on glass at about 225,200 lines to the inch.

The **Unit Angle** in Rotation is the "**Radian**" = 57° 14′ 44″·8, the angle whose arc is equal to the Radius (Fig. 5).

One "**Centrad**" = $\frac{1}{100}$ radian; used in ophthalmology.

Fig. 5.

The **Mass** of an object is the **Quantity of Matter** in it. This is measured by the quantity of matter which it will counterpoise in a Balance. The **unit of mass** is the **Gramme**, which is the mass of one cubic cm. of water at 3·9° C. (39° Fahr.)

Decigramme = $\frac{1}{10}$ grm. ; centigramme = $\frac{1}{100}$ grm. ; milligramme = $\frac{1}{1000}$ grm.

Kilogramme = 1000 grms. = mass of 1 Litre of water at 3·9° C. = 15432·35 grains.

One Gramme = 15·43235 grains ; 1 Kilogramme = 2·20462 lbs.

1000 kgr. = 1 "tonne" = 2204·62 lbs. = 0·9842 English ton = 1·10231 American or "short" ton of 2000 lbs.

French 20 centimes silver = 1 centime bronze = 1 gramme.

German 1 pfennig bronze = 2 grammes.

U.S. dime = German 5 pf. nickel = $2\frac{1}{2}$ grammes.

German 10 pf. nickel = 4 grammes.

French franc = French 5 c. bronze = U.S. 5 c. nickel = 5 grammes.

French 2 fr. silver = French 10 c. bronze = 10 grammes.

Thus grammes may be weighed out with newly-coined French bronze coinage at 1 gramme per centime.

- One lb. avoirdupois = 16 ounces = 7000 grains = 453·593 grms. = $\frac{1}{10}$ British gallon of water at 62° F.
- One oz. avoird. = 1 fluid oz. water at 62° F. = 28·34956 grms. = $437\frac{1}{2}$ grains.
- Three British pennies (new) = 1 oz. avoirdupois.
- One grain = 0·064799, or nearly 0·0648 gramme.
- One British gallon = 10 lbs. water at 62° F. = 8 pints = 277·274 cub. in. = 4·53228 litres.
- One British pint = 20 fl. oz. = $1\frac{1}{4}$ lb. water at 62° F. = 0·566535 litre.
- One fluid ounce = 1 oz. avoird. of water at 62° F. = $\frac{1}{20}$ British pint = 227·1642 cub. cm.
- American gallon = 8 lbs. water ; American pint = 1 lb. water.

For prescriptions, etc., the grain is at present the basis ; 480 grains = 24 scruples = 8 drachms = 1 Old Apothecaries' ounce. The old apothecaries' ounce is not now in use, except in prescriptions ; "an ounce" of any chemical, bought at a chemist's, is the avoirdupois ounce of $437\frac{1}{2}$, not of 480 grains.

The fluid ounce (= $437\frac{1}{2}$ grains weight of water at 62° F.) is divided into 8 fluid drachms, or 480 minims. Each minim of water, at 62° F., weighs 0·901146 grains.

In **solutions**, say of "10 per cent" strength, distinguish as follows: A solution, say of bromide of potassium of "1 to 10" is KBr 1 gramme, water 10 grammes or 10 cub. cm.; or KBr 1 oz., water 10 fluid ounces (=10 oz. wt.) A solution of "1 in 10" is KBr 1 grm., water 9 grms. or 9 cub. cm. These assume that for use the solution is to be weighed out. But when the solution is to be measured out, the possible difference in volume between the water used and the solution produced has to be kept in mind. Hence, for measuring out, "1 in 10" would be 1 part by weight of the salt contained in 10 parts by volume of the solution; thus take KBr 1 gramme, water to make up to 10 cub. cm.; or KBr 1 oz., water to make up to 10 fl. oz.; and read the quantity, measured out in cub. cm. or in fl. oz. of the solution, as fractions of a gramme or of an avoirdupois ounce of the salt dissolved. Frequently what is wanted is "1 grain in 10 minims"; for this take KBr one apothecaries' ounce (=480 grains), water to make up to 10 fl. oz.

The **unit of time** is the **Second.**

This is $\frac{1}{86400}$ the average length of a **solar day**, that is, from noon to noon; noon being the time when the sun, lying directly south, is highest in the heavens.

CHAPTER II

MOTION OF BODIES

There are three ways in which a body may move: it may undergo **Translation**, mere travelling from one place to another along a straight or a curved path; or it may **Rotate** round some axis either within its own substance or outside the same; or it may **become deformed**, and if it be deformed it may or may not ultimately regain its original form, or nearly its original form, with or without **Vibration**; and it may do any or all of these things simultaneously.

A minute **particle** is said to have **three degrees of freedom** to move: it may, for example, move up-and-down, side-to-side, or fore-and-aft. If it be restricted to a given surface, it has only **two** degrees of freedom, for it cannot leave that surface; if it be restricted to one surface and at the same time to another surface, it can only move back-and-fore along the line where these surfaces intersect, and has only **one** degree of freedom. A **body**, as distinguished from a particle, has these three degrees of freedom and also three others: it can **spin**, for example, round an axis situated up-and-down, an axis lying from side-to-side, and an axis lying fore-and-aft. If one point of the body, and one point only, be held fixed, the body can rotate in any way round axes passing through that point. If two points be held fixed, the body can rotate round an axis which passes through these two points. If three points be held fixed, it cannot move at all.

If a piece of apparatus be mounted on **three sharp points** laid in conical sockets on a baseboard, it can be lifted off the baseboard, and it can always be put back in the same position on that board. If its lower face bear a **V-shaped** projection, and if this be laid in, or better, pressed by a spring into a corresponding V-shaped hollow in the baseboard, the apparatus can only slide to-and-fro along the groove, or else be lifted or tilted off the board; and when the V-shaped projection is run up against a **stop-pin** in the V-shaped groove, the position of the apparatus is again definite with respect to the board. The same fixation by deprivation of degrees of freedom may be seen in aseptic **removable knife-blades**, interchangeable in a **spring-handle.**

In what follows we shall first concern ourselves with the movements of **Translation** of a body.

Translation

In every body or object there is some point whose position is the average of all the positions of all the several particles of the body. This point is called the **Centre of Figure** of the body. Again, in every body there is some point which corresponds to the average position of the whole Matter of which the body is made up; and this point is called the **Centre of Mass.** If the body be of **uniform** substance throughout, the Centre of Figure and the Centre of Mass of the body are **identical**; if not, the centre of mass and the centre of figure may be at different points, as in the case of the moon, which is to some extent like a loaded billiard ball, heavier towards one side though symmetrical in form, and therefore having its centre of mass, as it were, displaced towards the heavier side.

When **parallel** Forces act on the several particles of a body, on each in proportion to its Mass, the aggregate result is as if a **single force** had acted on a single particle situated at the **centre of mass**; and the body as a whole undergoes a corresponding Translation. When we say that a material body undergoes **Translation**, we may therefore confine our attention to the movements of its **centre of mass**; and this simplifies matters considerably.

When a body moves in a Straight Line, its Direction of Motion is the **straight line** itself. When it moves in a Curve, its direction of motion at any point of that curve is the direction of the **tangent to the curve** at that point. In Fig. 6, when the body is at the point P in the path AB, the direction of movement is for the moment in the direction PC: PC is "the tangent to the curve" at P.

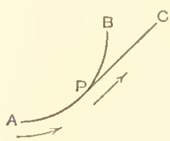


Fig. 6.

The **Velocity** of a moving body, moving uniformly in any direction, is the **number of cm.** traversed by it **per second.** If it move 60 cms. in 10 sec., the velocity is 5 cms.-per-second. Of a body not moving uniformly, the "**mean velocity**" is the average velocity, the whole space traversed divided by the whole time: a railway train which reaches a point 36 kilometres away in one hour, has a mean velocity of 36 kiloms. per hour, or 1000 cms.-per-second. At any particular moment the train may, however, be covering say 40 metres in 2 seconds; during that time its velocity is 2000 cms.-per-second.

If a body be by any means affected with **two velocities simultaneously**, and if these velocities be constant in direction and amount, the result or "**resultant**" is a single velocity in a Straight Line.

Let a steamship steam eastwards and drift northwards simultaneously, starting from the point O. It will, in a given time, reach a point A which lies both so far to the north and so far to the east; in twice the time it will reach a corresponding point B: after successive equal intervals it reaches the points C, D, etc.; the points A, B, C, D, etc., all lie in a straight line, and that straight line describes the actual direction and velocity of movement of the steamship. The steamship travels along the line OD in the same time as it would have taken to steam to E or to drift to N if there had been no drifting or no steaming respectively. Therefore the Resultant of the two velocities is a single velocity along a line OD, which is the Diagonal of the Parallelogram OD (Fig. 7).

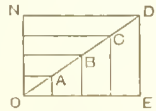


Fig. 7.

The angle NOE need not be a right angle: the resultant is still in a line, which is the Diagonal of the "**Parallelogram of Velocities**" (Fig. 8).

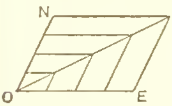


Fig. 8.

It is not necessary to draw the complete parallelogram: it will suffice to draw from O a line which, in magnitude and direction, represents one of the velocities; then from the other end of this line draw a line representing the other velocity. Join the free end of this line with O: the line thus drawn represents the **resultant** in its magnitude; and the resultant velocity is along that line, in a direction **opposed** to the direction of the **components** taken successively round this so-called **Triangle of Velocities**, as will be seen from the figure (Fig. 9).

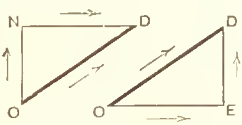


Fig. 9.

By reversing the process we may break up or "**resolve**" OD into its components in any two directions. Let the problem be to resolve OD into components in any two given directions GH, IJ. From O draw a line parallel to one of these directions, and from D draw a line parallel to the other; these two lines cross one another in the point E. Mark the lines OE and DE with arrows opposed, in their direction round the triangle, to the direction of OD; the lines OD and ED represent the components sought for.

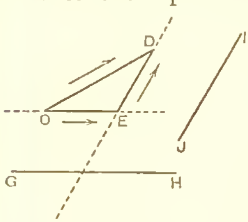


Fig. 10.

If we know two sides of the triangle of velocities it is always easy to **find the third side**. For example, suppose we know the actual course of a steamer to be, that it is travelling with uniform velocity in the direction OD (Fig. 11): but we also know that it is being steered in the direction OE, so that in the same time it ought to have reached E: what is the drift? It is represented by the line ED. The addition of a drift more or less directly **athwart** the line in which the

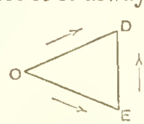


Fig. 11.

boat is being steered gives the actual movement a **different direction.**

Two **equal and opposed** velocities **balance** one another, and the resultant velocity is **nil.** If a man walk astern on board a ship at the rate of 4 miles an hour while the ship is sailing at the same rate, he will be really marking time in the same place.

The **Momentum** of a body is the product of its **mass** (in grammes) into its **velocity** (in cms.-per-sec.)

If a shell explode while travelling in a particular direction, the aggregate momentum of the fragments in that direction is the same as that of the shell.

Let two bodies, freely suspended, strike one another: if they be **inelastic** they divide their joint momentum and move in the same direction with a **common velocity**; if we could obtain perfectly **elastic** balls, such balls would, upon collision in a line joining their centres, **recoil** from one another, the one gaining by the collision as much momentum as the other loses; and two **equal and perfectly elastic** balls, striking one another directly in the line joining their centres, would **exchange** their **velocities.** If balls strike one another otherwise than directly in that line, they will **spin** as well as rebound. A perfectly elastic ball would **rebound** from a wall with the **same speed** as it reached it, and the momentum would be the same as at first, but reversed in direction; that is, assuming that there were no vibration or spin set up in that ball; but in actual cases the ball rebounds only with a certain **fraction** of the original velocity; and this fraction is called the **Coefficient of Restitution.**

Acceleration.—This is a **gain or loss** of **Velocity, per second.**

A train, making up speed from 36 kiloms. to 54 kiloms. per hour in five minutes, gains speed, in the course of 300 seconds, to the amount of 18 kiloms. per hour, or 500 cms.-per-sec. If the gain in speed be uniform, the train gains in velocity to the amount of $1\frac{2}{3}$ cm.-per-sec., during each second; and, as the phrase goes, its Acceleration is $1\frac{2}{3}$ cm.-per-sec. per second. If, on the other hand, it slacken down in the same time from 36 to 18 kiloms. per hour, it undergoes **retardation** or **negative acceleration**; and its Acceleration is said to be $-1\frac{2}{3}$ cm.-per-sec. per second, a negative quantity. If there be no acceleration, positive or negative, the velocity remains unchanged.

The Acceleration (in cms.-per-sec. per second) is usually represented by the symbol a.

If v_o be the original velocity in a given direction, v_t the velocity attained in the same direction at the end of a certain time t seconds; and if s be the space traversed during the time t: the relation between these terms v_o, v_t, t, s, and the uniform Acceleration a (or retardation $-a$ as the case may be) are given by the equations:

$$v_t = v_o \pm at \qquad (1)$$

$$s = v_o t \pm \tfrac{1}{2}at^2 \qquad (2)$$

$$v_t = \sqrt{v_o^2 \pm 2as} \qquad (3)$$

Examples.—(1) Let a body fall from rest ($v_o = 0$) from the top of a cliff 100 metres ($s = 10000$ cm.) high: what speed will it attain just before reaching the ground, and how long will it take to reach the bottom? Note, as a fact, that a falling body gains a velocity of **981** cm.-per-sec. in one second, 2×981 cm.-per-sec. in two seconds, and so on: that is, for a falling body, $a = 981$ downwards. The problem therefore is, given v_o, s, and a, to find v_t and t. To do this we must pick out the most useful of the three equations above. The third equation is $v_t = \sqrt{v_o^2 + 2as} = \sqrt{0 + (2 \times 981 \times 10000)} = \sqrt{19620000} = 4429$ cm.-per-sec., the velocity ultimately attained. The first equation is $v_t = v_o + at$; that is, $4429 = 0 + 981t = 981t$; and $t = \frac{4429}{981} = 4{\cdot}51$ seconds, the time taken to fall the given height.

(2) Let the same body be thrown down from the top of the cliff with an initial velocity of 20 metres per second ($v_o = 2000$ cm.-per-sec.) Then $v_t = \sqrt{(2000)^2 + 19620000} = \sqrt{23620000} = 4860$ cm.-per-second; and $4860 = 2000 + 981t$; whence $t = 2{\cdot}91$ seconds.

(3) Let the same body be shot up from the top of the cliff with an upward velocity of 20 metres per second ($v_o = -2000$ cm.-per-sec.); v_t is again 4860 cms.-per-sec., because $(-2000)^2$ is equal to $(+2000)^2$; but in the first equation $4860 = -2000 + 981t$; whence $t = 6{\cdot}99$ seconds. The body, sent upwards with an upward velocity of 2000 cms.-per-sec., ascends, comes to rest for an instant, and falls back, passing the starting-point with a downward velocity of 2000 cms.-per-sec.

(4) A cricket-ball is thrown up into the air. It rises say 30 metres ($s = 3000$ cm.) What is its initial velocity? What time will it take to ascend? Here the acceleration is **negative**, being opposed to the direction of the initial motion; it is therefore -981 cms.-per-sec. per second; and the body

rises until it has no velocity, and is "on the turn" (*i.e.* $v_t=0$). Hence the problem is, given s, a, and v_t, find v_o and t. From equation (3), $0=\sqrt{v_o^2-(2\times 981\times 300)}=\sqrt{v_o^2-588600}$; $v_o^2=5886000$; $v_o=2426$ cms.-per-second, the initial velocity. From equation (1), $0=2426-981t$; whence $t=2{\cdot}47$ seconds, the time taken in the ascent.

(5) A train travelling at 72 kilometres (say 45 miles) an hour is abruptly stopped by a collision: what height would the passengers have had to fall in order to receive a similar blow? That is, what height would they have had to fall from rest ($v_o=0$) before the speed attained would be 72 kiloms. per hour ($v_t=2000$ cms.-per-sec.)? Here we know v_o, v_t, and a, and we want to find s. By the third equation, $2000=\sqrt{0+(2\times 981\times s)}=\sqrt{1962s}$; $1962s=4000000$; $s=2038$ cm. or $20{\cdot}38$ metres (say 67 feet), the required height of fall.

(6) If a man step out of a car running at 266 cms.-per-sec. (6 miles an hour), and do this at a run so that he takes two seconds to stop, what must be the retarding acceleration? What must it be if he stumble and have to recover himself within $\frac{1}{10}$ sec.? In the first case, $v_o=266$, $v_t=0$, and $t=2$, whence $a=-133$ cm.-per-sec. per second. In the latter, $t=\frac{1}{10}$; whence $a=-2660$, twenty times as great. The effort necessary to cause such a prompt pull-back, or negative acceleration, sometimes fractures bones.

If a body moving in one direction be subjected to an acceleration in another, lying more or less **athwart** its direction of motion, it swerves from its course.

A body A moving in a **circle** is continuously subject to an **acceleration** always at right angles to its direction of motion at any and every instant, that is **towards the centre** of the circle; and this Acceleration (in cms.-per.-sec. per second) is equal to v^2/r, where v is the actual Velocity (in cms.-per-sec.) in the circle, and r is the length (in cms.) of the Radius of that circle. If it had not been for this acceleration the body would, after leaving any given point, say A, have travelled straight on in the direction AB, the **tangent** to the circle at that point A. So for every other point; at every point the path is bent inwards; and the circular path is the resultant of the composition, at each point, of a tangential path with a fall or movement towards the centre.

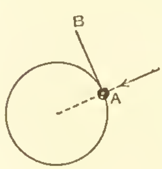


Fig. 12.

If a body be by any means subjected to different accelerations **simultaneously**, what is true of Velocities in general is true of velocities-imparted-in-unit-of-time, that is, of Accelerations; and thus we have a series of propositions concerning the **composition** and **resolution** of Accelerations exactly parallel to the similar propositions concerning the composition and resolution of Velocities.

Force.—The product of the **Mass** of a body (in grammes) into its **Acceleration** (in cms.-per-sec. per second), if it have any, is called the **Force** supposed to be acting upon the body, so as to make it go faster or slower, or to change its direction of motion. If there be no acceleration there is no Force acting. The unit of Force is called a **Dyne**, and the Dyne is the Force observed when a **gramme**-mass gains or loses a **unit velocity** (1 cm.-per-second) during **one second**; that is, when a Unit Mass undergoes a Unit Acceleration.

In a particular case Force has a special name. When a body is allowed to fall freely in a vacuum, it gains steadily in speed, acquiring a velocity of 981 cms.-per-sec. at the end of one second, twice 981 at the end of two seconds, and so on. The acceleration downwards is therefore 981 cms.-per-sec. per second, whatever be the mass of the falling body. The downward Force acting on say 10 grammes is the product (Mass × Acceleration) $=(10 \times 981)=9810$ dynes; and the force acting on 1 gramme $=981$ dynes. This downward Force of Gravitation, acting on any given mass, is called the **Weight** of that mass; **the Weight of one Gramme is equal to 981 Dynes**; whence the Dyne is found to be $\frac{1}{981}$ the weight of one Gramme.

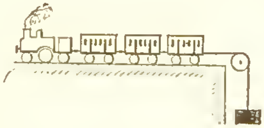


Fig. 13.

The above statements regarding Force imply that the body **moves freely.** But take the case of a railway train running on a level; it does not run freely; it continuously tends to **slacken speed** by reason of **Friction**, exactly *as if* it had a **heavy mass** of say 1 kilo. per 320 kilos. (= say 7 lbs. per ton) of train-load to

pull vertically up over a pulley ; and if the train run at a uniform velocity, the duty the engine is performing is that of **preventing slowing off** in speed.

Let the train weigh 160 tonnes of 1000 kilogr. each ; the retarding force is equal to the Weight of $\frac{160}{320}$ tonne or 500 kilogr. or 500,000 grammes. This Weight is equal to 500,000 $\times 981 = 490,500,000$ dynes ; and the engine must exert a pull equal to 490,500,000 dynes in order to neutralise the retarding force of friction and keep the speed constant. The Weight of 500,000 grammes, considered as a retarding Force acting on a mass of 160,000,000 grammes, would have produced a backward or negative acceleration a ; this is prevented by the force exerted by the engine ; this force $F =$ the mass acted upon $\times a$; that is, 490,500,000 dynes = 160,000,000 grammes $\times a$; hence $a = 3{\cdot}065625$ cm.-per-sec. per second. The Force exerted by the engine is the product of the mass moved into the acceleration **prevented**, which is 3·065625 cm.-per-sec. per second.

If the train gain speed, the force or pull exerted by the engine is the product of the whole mass of the train into the negative acceleration prevented, **plus** that of the mass into the positive acceleration produced. Let the engine work up speed steadily, so as to gain a velocity of 18 kiloms. per hour in 5 minutes ; the acceleration produced is $\frac{5}{3}$ cm.-per-sec. per second ; the product of this into the mass is the force producing acceleration, namely $\frac{5}{3} \times 160,000,000 = 266,666,666$ dynes. The sum of this and the preceding is 757,166,666 dynes ; and this is the total Force or pull exerted during the gain of speed. The pull upon the couplings is therefore the same approximately, whatever the speed may be, provided that the speed remains uniform ; but the pull upon the couplings is increased when the train is gaining speed, and falls off when it is slackening.

But there may be cases in which there is no movement whatever, and therefore no acceleration ; in such a case all that a Force does is to **prevent** an opposite **acceleration** being produced by an opposing force.

Take the case of two **wrestlers**, equally strong and at equal grips ; they may exert violent pressure upon one another without being able to push or displace one another a single inch. Take the case of a **stone held in the hand** ; the stone continuously tends to fall, but yet does not fall ; neither does the hand lift the stone. In the latter of these two cases the Weight of the stone would, were it not for the hand, result in a downward motion of the stone; on the other hand, the upward Pressure exerted by the hand would, were it not for the weight of the stone, result in the stone being hurled upwards. Between the two tendencies the stone remains at rest; if either of these flagged the stone would move; but as the tendency downwards, the so-called gravitational attraction or the Weight, is unflagging and unwearied, the natural result is that the hand may grow wearied and flag in its upward pressure, and then the stone will sink or fall. So long, however, as the hand can hold out, there is equilibrium between the downward Weight of the stone and the upward Pressure of the hand, and each of these prevents the Acceleration which the other tends to produce.

Where a man faints and is about to fall to the ground, and others help him by letting him down easily, they exert an upward force which partially prevents that downward acceleration which gravity tends to produce.

Let a man fix a stout **spring** into a wall and slowly **pull** the other end towards himself. At first he can pull it. There is a **resisting counter-force** which pulls against him; but he can overcome this. As he pulls, and the deformation of the spring increases, the resisting force goes on increasing. At length the resisting counter-force becomes equal to the task of preventing him from pulling the spring out any farther. At this moment we have the spring pulling the man and the man pulling the spring; and neither of them is then able to make the other move. The force exerted by the man and the counter-force exerted by the spring are then in **equilibrium**; they are equal and opposite to one another.

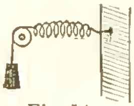


Fig. 14.

To the spring it does not matter, nextly, whether the stretching force be exerted by a man or by the weight of a sufficiently heavy body, as in Fig. 14; and if a **weight** be applied, as in the figure, such as will **stretch** the spring to the **same extent** as the man had done, we at once find the value of the Force exerted by the man.

For example, let the weight required to produce an equal extension of the spring be the weight of 80 kgrs., or 80,000 grammes; then the man's force was $80{,}000 \times 981 = 78{,}480{,}000$ dynes. Conversely, if that man apply this maximum force of his to the task of pulling up heavy masses by means of a cord slung over a pulley, supported by any convenient means, he can only lift 80 kgrs. off the ground; and the weight of a mass of 80 kgrs. on the one hand, and on the other hand the counter-force of the spring at the fullest extension of it which the man can compass, are equivalent and equal.

We may therefore **measure** Forces by finding the **deformations** which they can produce in springs, and then ascertaining what **weights** are required in order to produce the **same deformations**.

For example, in estimating the power of grasp of the hand in the diagnosis of nervous diseases, such as partial or general paralysis, an instrument called a **dynamometer** is used, in which the hand is set to squeeze a spring out of shape: the deformed spring actuates a pointer which points to a certain figure on a scale; and the scale is graduated in terms of the different weights which, acting upon the same spring, will produce the same deformations of that spring. The same principle is applied in the common **spring balance**, in which known weights produce known deformations; and the weight of a given body or the value of any given pull may thus be read off on a scale attached to the instrument.

A stretched spring is in a condition of **stress**: it pulls upon both its ends equally and oppositely.

A compressed spring, again, is in a condition of stress: it pushes both its ends apart, equally and oppositely.

In every case where Force is exerted there is a condition of Stress: for wherever an object A is pressed or pulled towards or from or attracted towards or repelled from an object B, the object B is equally pressed or pulled towards or from or attracted towards or repelled from the object A. As Sir Isaac Newton put it: "To every action (*i.e.* to every Force) there is always an equal and contrary Reaction; or the mutual actions (*i.e.* forces) of any two bodies are always equal and oppositely directed." The **force** acting upon A and the **opposite force** acting on B are **equal**; but if the Masses of A and B be not equal the respective Accelerations of the two bodies towards one another will not be equal; for it is, in regard to each of the objects A and B, the Force, that is the *product* of the Mass into the Acceleration, which is the same in both.

If a light and a heavy ball be connected by an indiarubber cord, and if they be pulled apart and let go simultaneously, each will move towards the other, but the **heavier** one will move **more slowly.**

When a **shot** is fired from a **gun,** if the gun be free to move, the shot moves forwards and the gun moves slowly backwards. If the bullet and the gun had been of equal weight, they would have flown apart with equal velocities; and, short of this, the heavier the bullet the greater is the tendency for the gun to fly backwards upon discharge.

The **earth** attracts the **moon** and the moon equally attracts the earth; but the moon, being the lighter of the two, has more acceleration towards the earth than the earth has towards it.

When a **stone** is thrown upwards from the **earth,** the earth is equally thrown downwards: but the earth is so much larger than the stone that its downward movement is inappreciably small. Similarly a **man** pushes the **earth** down at every step: Archimedes needed no lever to move the Earth. If the earth be soft locally, the pedestrian's foot is driven into it as it yields; and in boggy soil every effort causes him to sink more deeply.

When a **horse** is inexperienced he may be found trying to pull a heavy **tramcar** suddenly forward with a jerk; but as the traces tighten, he is jerked backwards as much as the car is jerked forward, and with a greater acceleration on account of his smaller weight. When a **locomotive** is suddenly started with a heavy **train** the wheels may go round uselessly; the reaction of the train is equivalent to a backward pull upon the locomotive, considered as already in motion.

Pressure.—If we rest a heavy body on a surface it produces Pressure, which is equal to its own Weight in dynes: and pressure produced by any cause may be measured in dynes, by comparison with the Weights which can produce the same effect. Such pressure is a **Total Pressure,** and does not depend on the area of the body pressed upon; but Pressure is also often specified as an Intensity of Pressure, or a Pressure of so many dynes per sq. cm. of Area.

The distinction between a Total Pressure and a Pressure per sq. cm. of Area is a matter of importance. **Cutting instruments**, such as knives, chisels, or scissors, are instruments with a very restricted area or areas, through which the pressure of the hand may be exerted: and when we "sharpen" a knife we diminish the area of its edge. The cutting power of a knife depends directly on the pressure per sq. cm., which may become extremely great when the knife is extremely sharp. A **blow** on the skull by a **round stone** may subject the scalp to pressure over a very small surface, and cause it to give way almost as if it had been cut with a knife. A person finding himself straying into a **quicksand** or into boggy soil should throw himself down horizontally and creep back into safety, for he is not so likely to sink when he lies on a broad surface as when his weight is concentrated upon the narrow surface afforded by his feet alone. A person does not sink in snow when his weight is distributed over a large area by means of large Canadian **snow-shoes**. Ice will bear a plank with a man standing upon it, when it could not bear the weight of the man standing directly on the bare ice; and **sledges** can travel over snow in which cart-wheels would sink. In **massage-rollers** there are grooves and comparatively sharp annular protuberances between these; when the roller is used, the local intensities of pressure are comparatively great. The penetrating power of a **needle** depends on the intensity of pressure; and it is greater if the needle have a triangular section, so that it presents cutting edges. When the weight of the body is borne by limited areas of the skin, the intensity of pressure may be great: whence **bedsores**, etc., and the necessity of even support uniformly applied, as in a **water-bed**, which is, mechanically, an appliance for equalising the intensity of pressure over the whole area of support.

Tension.—If we hang a mass m grammes on a wire, we cause a **Pull** or **Tension** in that wire equal to the Weight of the suspended mass, that is 981 m dynes. For comparison it is often convenient to find the cross-sectional area of the wire, and to state the tension as a "**traction**" of so many dynes per sq. cm. of cross-sectional Area.

Thus if we hang 50 grammes upon a wire whose cross-section has an area of $\frac{1}{100}$ sq. cm., the Total Tension is 49050 dynes; and the tension per sq. cm. is $(49050 \div \frac{1}{100}) = 490500$ dynes per sq. cm. Where a cord, stretched by a weight, happens to be thinnest, there the tension per sq. cm. of cross-sectional area is greatest; and there, at the thinnest part, the cord has most tendency to give way and snap.

Centrifugal Force.—Suppose a stone to be whirled round, like a slingstone, by means of a string, but in a perfectly circular path. The **acceleration** towards the Centre is (p. 12) equal to v^2/r, the square of the velocity divided by the radius: the **force** acting upon the stone, to make it travel in the Circle and not escape along some Tangent, is mv^2/r dynes, where m is the mass of the stone, in grammes. In the case of the slingstone this force is exerted by means of the **tension** of the string: and if the Velocity exceed a certain limit, this tension will become too great, and the string will **snap**. The stone will then fly off at a tangent.

A fly will be hurled off a rapidly rotating wheel, for it cannot adhere firmly enough to the rim by means of its feet. The cohesion of a rapidly rotating **wheel** may fail, and the wheel fall to pieces, each of which flies off at a tangent. If the **earth** rotated seventeen times as fast as it does, loose objects would fly off its surface at the Equator: their weight would then fail to hold them down. **Railway trains** tend to fly the track as they come rapidly round curves, and to run off at a tangent: the pressure of the flange on the outer rail prevents this.

A **drop of oil**, rotated, spreads out into a flattened spheroid; and for the same reason the **earth** is itself an oblate spheroid, its Polar axis being the shortest. In the trundling of a **wet mop** the drops fly off. If a man were placed on a **revolving table**, with his feet towards the centre, the blood in his body would be impelled towards his head; and this has actually been proposed as treatment for anæmia of the brain.

When light and heavy particles are mixed and whirled the heavier fly outwards: thus milk is separated by a "**centrifugal machine**" from cream, or blood corpuscles from blood plasma.

The **circus rider** stands on horse-back slanting inwards. His own weight tends to make him fall inwards: centrifugal force tends to throw him off on the other side: his actual position is one of equilibrium between these two tendencies.

Resolution of a Force.—Where a force acts in a particular direction, the motion or pressure or tension produced in another direction is ascertained by "resolving" the force in the direction in which that motion or pressure or tension is to be ascertained or measured.

For example, if the body is thrown forward and upward in **walking**, the forward and the upward components of the force may be considered separately: the former gives the body a forward motion; the latter acts as if it were a single force lifting the body against its own weight. When a child's head is being delivered by **midwifery forceps**, the pull on the head by means of the forceps is inclined at some 29° to the maternal passages, and the effective component along these passages is less than the pull exerted by the accoucheur. At the same time the other component is one at right angles to the walls of the maternal passages, and induces a detrimental pressure. On the principle that two sides of a triangle are greater than the third side, it will be seen that the resultant components, if added together, would seem to be greater than the force applied; but it is not a legitimate mathematical operation so to add them together, for forces in different directions cannot be added. They may, however, be compounded. For example, the two forces AB, AD of Fig. 15 may be compounded into their resultant, represented by the diagonal AC.

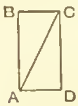


Fig. 15.

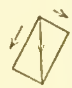


Fig. 16.

Work.—This is the *product* of the **force** acting or overcome into the **space** through which it acts or is overcome. The C.G.S. unit of work is the **Erg** = one dyne × one centimetre.

Examples.—(1) The mean pressure of steam on the piston in a steam-engine is, say, equal to the Weight of 1000 grm. per sq. cm.; the area of the piston is, say, 480 sq. cm.; the stroke of the piston is, say, 60 cm. What is the Work done at each stroke? It is the product of the whole mean force or pressure, $[(1000 \times 981) \times 480]$ dynes, into the stroke 60 cm.; it is therefore $(1000 \times 981 \times 480) \times 60 = 28,252,800000$ ergs.

(2) Let a man whose weight is 72 kilogr. (say 11 st. 4½ lbs.), and who presents an area of say 4500 sq. cm. to the wind, make his way through 1·6 kilom. (=1 mile nearly) against a storm which produces a mean pressure equal to the weight of 2½ grammes per sq. cm. (=about 50 lbs. per sq. ft.): what Work must he do against the wind? The Pressure overcome is $(2·5 \times 981 \times 4500)$ dynes; it is overcome through 1600 cm.; the Work done is $(2·5 \times 981 \times 4500 \times 1600) = 17658,000000$ ergs.

(3) To what Height would the same work have lifted him vertically? In that case the Force resisted would have been his Weight, $(72,000 \times 981)$ dynes. The Height = the Work ÷ the Force resisted $= \frac{17658,000000000}{70,632000} = 250000$ cm. $= 2500$ metres $= 8202$ ft. From this we see how unexpectedly great an effort it is to battle against heavy wind.

(4) If the mean or average force required to pull a vehicle along a rough road be equal to the weight of 50 kgr. when there are no elastic springs between the draught animal and the vehicle, and of 40 kgr. when there are, what is the ratio between the amounts of Work which must be done in pulling the vehicle a given distance in the two cases? Here the space traversed is the same in both cases, and the work is proportional to the mean forces directly: that is, it differs in the two cases in the ratio 50 : 40.

English engineers usually measure Work in **foot-pounds.** This is again the product of the Space traversed (feet) into the Force acting (pounds); but the Force acting is measured as so many units of Weight.

On this method a Force equal to the Weight of 10 lbs. is called a force of 10 lbs. This would be satisfactory were it not that the weight of a lb.-mass is a bad unit of Force, for it is not constant from place to place; but the error is barely over $\frac{1}{2}$ per cent over the earth's surface.

Example.—The mean pressure of steam on the piston in a steam-engine is equal to the weight of say 30 lbs. per sq. inch: the area of the piston is say 30 sq. inches; the stroke of the piston is say 16 inches. What is the Work done at each stroke? It is the product of the whole pressure (equal to the weight of $30 \times 30 = 900$ lbs.) into $1\frac{1}{3}$ feet; it is therefore $900 \times 1\frac{1}{3} = 1200$ foot-pounds.

When the acceleration of gravity is 981 cm.-per-sec. per second, one foot-pound $= 13,562,691$ ergs.

The maximum work that **muscle** (*i.e.* frog-muscle) appears able to do at each contraction is such as would raise its own mass 400 cm.; that is, $400 \times 981 = 392400$ ergs per gramme of muscle.

The circumstance that the Work done is equal to the product of the Force into the Space traversed enables us, in many cases, knowing the Work done and the Space traversed, to **measure the force** acting. The **work** which we can make any mechanical contrivance do is **never greater** than the work which is expended upon it; and if any contrivance be so made as to enable us to get a given amount of Work done by a **longer** and less direct **path**, we find it easier to do that work, for the **force** along the longer path is **less** in proportion to the increased length of path.

In an **Inclined Plane**, suppose a heavy body is **pushed** up from A to B, where AB = 61 cm., so as to make it gain vertical height equal to CB = 11 cm.; the Work done (apart from friction) = Weight of the body × 11 cm. But this has been effected by exerting a force less than the Weight, through a greater distance AB; the Force exerted up the slope is therefore $\frac{BC}{AB}$ times the Weight of the body lifted: in the instance supposed, it is to the Weight of the body lifted as 11 : 61.

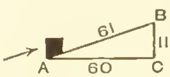


Fig. 17.

If the force applied be kept **parallel** to AC, on reaching the top the horizontal force will have been kept up through a horizontal distance AC (= 60 cm.); the force exerted horizontally is therefore smaller than the Weight of the body, in the ratio 11 : 60.

If the inclined plane be pushed under the heavy body, a movement of the wedge horizontally through, say 6 cm., would correspond to an upward movement of the heavy body through 1·1 cm.; and the Force necessary to accomplish this would be $\frac{11}{60}$ the Weight of the heavy body. This is the principle of the **wedge**. In practice more work than this would have to be done on account of friction; but friction is useful in respect that it prevents the wedge from slipping back.

The thread of a **screw** corresponds, as may be seen in any specimen, to a narrow inclined plane wrapped round a cylinder. In a **copying-press**, say of arms 12 inches each, screw $1\frac{1}{2}$ inch thick, with threads $\frac{1}{8}$ inch apart, when either hand moves through 1 inch the point of the screw moves $\frac{1}{648}$ inch: hence the Force which can be exerted by such a screw-press is 648 times that which can be directly applied by the hands. This is applied in **table-clips**, in **presses** for separating muscle juice from muscle, in clipping the points of **forceps**, etc.

The Screw is also used as a means of **measuring small thicknesses**. For example, in measuring the thickness of a microscopic **cover-glass**, the cover-glass is grasped by a pair of separable steel jaws whose mutual position is controlled by a screw. If the screw have 20 threads to the inch, each turn of the screw will separate the jaws through $\frac{1}{20}$ inch; and if the screw-head (which is made of sufficient size and is graduated) have to be turned back through say 65° in order to enable the cover-glass to be grasped between the movable jaws, the thickness of the cover-glass is $\frac{65}{360} \times \frac{1}{20} = 0·009$ inch. When the screw-head is turned through equal angles (*e.g.* when successively equal numbers of teeth on a milled head are caught by a pawl and ratchet and arm) we have equal amounts of travel of the screw in its nut; and this is applied in the **Microtome,** an instrument for cutting successive very thin slices of tissue (as thin as $\frac{1}{40000}$ inch) for microscopic examination; and in the **Dividing Engine,** which makes marks at equal distances apart upon a scale or tube which it may be desired to graduate, as in the ordinary thermometer. The pushing in of a wedge to a greater or less extent in some **fine adjustments** of microscopes, etc., essentially depends on the same principle. A vernier may be used at the edge of a large graduated screw-head in order to ascertain precisely what the rotation of the screw is.

In the **Differential Screw** (Fig. 18) we have two screws of different pitches cut on the same rod. A is a milled head: B is a fixed nut: C is a movable nut kept apart from a fixed base E by the springs D, and prevented from rotating. Let the upper part of the screw have 10 turns to the inch and the lower part 12 turns. Let the milled head be turned, so as to lower the screw as a whole, through one complete turn; the screw as a whole descends $\frac{1}{10}$ inch, and tends to carry C down through that distance. But C, being pushed upwards by the springs, and not being able to rotate, tends to travel upwards as against the descending screw: it can only do this, however, through $\frac{1}{12}$ inch. On the whole, therefore, C is carried downwards $\frac{1}{10}$ inch *less* $\frac{1}{12}$ inch $= \frac{1}{60}$ inch for each complete turn of the milled head. This construction, which is sometimes used in microscope adjustments, enables relatively coarse and strong screw-threads to be used for delicate work.

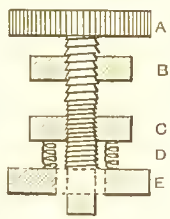


Fig. 18.

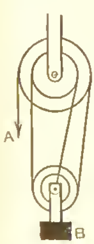


Fig. 19.

In **Pulleys** there are many varieties of form; but in all cases we may ascertain the ratio between the Force applied by the operator and the force transmitted by the machine, by finding the ratio between the Space traversed by the hand at A and the space traversed by the pulling hook or ring attached to the pulley at B. If B move upwards through 1 inch when the hand pulls A downwards through 8 inches, B is pulled up with a force 8 times that applied to A.

In the **Knee** the same principle is applied. When the rod AB, jointed at O, and sliding between guides at A and B, has its joint O pressed in, so as to straighten the rod or knee AB, a considerable movement of O corresponds to a very small movement of A and B. This is utilised in some copying-presses, railway-ticket endorsing machines, etc. On the same principle the pull on the walls is great and the tension of the wire considerable when an overhung **telephone wire** is swung by the wind.

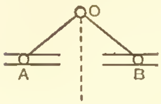


Fig. 20.

Another form of pressing apparatus is that of Fig. 21. OA is a lever jointed at O; the lower part is fashioned so that the plate BC is pressed farther down the farther A is pushed over, for the radii of the curve at the bottom of the lever, round the point O, increase steadily from point to point. A contrivance with varying radii is called a **cam**. As before, the ratio between the movement of the hand at A and that of the plate BC gives the mechanical advantage of the device.

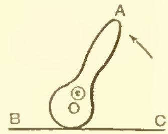


Fig. 21.

In many surgical instruments the same principle is illustrated. In all cases the mechanical advantage is the ratio between the travel of the hand and the travel of the ultimate moving part of the apparatus. For example, in **bone pliers**, if the hand contract through 3 inches, while the blades move through $\frac{1}{2}$ inch, the mechanical advantage is $3 \div \frac{1}{2} = 6$. Where **scissors** present a form like that of Fig. 22, we have only to look at the small terminal blades and compare their relative movement with that between the thumb-ring and finger-ring A and B. We need not concern ourselves with the intermediate linkage. In **mouth-stretchers** the blades A and B are moved asunder by pushing up a plate C, which is propelled by a screw D: the screw exerts a great pressure upon the plate C; but the small movement of C as compared with the movements of A and B causes the mechanical advantage of the screw largely to disappear, so that the instrument is not as formidable as it looks. In **dissecting forceps** the point of the blade moves more than the fingers do, and the grip on the structures seized is relatively lax; while with forceps of the ordinary kind, the grip by the short arms is firmer than the squeeze of the hands on the long arms. In **stretchers**, *e.g.* kid-glove stretchers, the short arms separate as the long ones are squeezed together: and the same principles

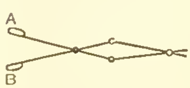


Fig. 22.

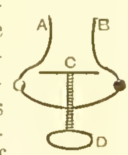


Fig. 23.

apply. Where **pincers** consist of **hooks** pulled through a **tube**, when they have taken hold a very small mutual approximation of the hooks will correspond to a much greater pull through the tube; and the transverse grip of such appliances is very firm. Where a **snaring-wire** is pulled through a tube, the amount by which the wire is pulled through the tube is usually greater than the distance by which the wire cuts through the polypus; and it is greatest, and the appliance accordingly most effective, when one of the two ends of the wire is fixed while the other is pulled through.

Fig. 24.

Activity.—The **work done per second** is called the **Activity**; and this is equal to the product of the Force, acting or overcome, into the Velocity.

British and American engineers call 550 foot-pounds (=7459,480050, or in round numbers 7460,000000 ergs) per second a **Horse-Power**: they define it as 33,000 foot-pounds a minute. The *cheval-heure* of the French engineers is 75 kilogramme-metres or 7357,500000 ergs per second. But a **horse** could not keep up this rate of working: a good horse can do about 436 foot-pounds per second. A labourer can do from about 8 (lifting earth with a spade) to about 70 (treadmill exercise, lifting his own weight). But during a spurt a man may do work at a rate far greater than he can keep up.

Examples.—(1) Let a man weighing 90 kgr. (say 14 st. 2 lbs.) run upstairs rapidly, at such a rate as to gain height equal to 90 cm. (say 3 ft.) per second; what will be his Activity? His Weight × the Height gained per second = (90,000 × 981) dynes × 90 cm. per sec. = 7946,100000 ergs per second = 1·065 horse-power. This is far more than a horse can keep up, and is about seventy-six times what a labourer continuously lifting earth with a spade can sustain. The danger of **over-strain** to heavy people is thus obvious.

(2) In the railway train of p. 14, what is the Activity if the uniform speed be 36 kilometres per hour? This speed is 1000 cm.-per-sec.; and the retarding force overcome is, as we saw, 490,500000 dynes. The Activity is the work done per second; and this is equal to Force × Velocity, = 490,500000 × 1000 = 490500,000000 ergs-per-second = 65·8 horse-power. When the train puts on steam so that it begins to gain speed at the rate of $1\frac{2}{3}$ cm.-per-sec. per second, the force exerted by the engine is 757,166666 dynes, and at first the velocity is still 1000 cm.-per-second: so that the activity is at first 757,166666 ergs-per-second = 101·4 horse-power. When the speed has come up

to 54 kilom. per hour (=1500 cm.-per-sec.), the force exerted is still the same, but the activity is now Force × Velocity = 757,166666 × 1500 = 113575,0000000 ergs-per-second = 154·2 horse-power. When the engine ceases to urge the train beyond this speed, and contents itself with maintaining it, the retarding force falls back to 490,500000 dynes, and the activity is now 490,500000 × 1500 = 735750,000000 ergs-per-sec. = 98·6 h.-p.

There are other units of Work and Activity, not the C.G.S., but others, based on the so-called Practical System of Electrical Units. These are the **Joule** = 10,000000 or 10^7 ergs, and the **Watt** = 10^7 ergs-per-second. One British horse-power is thus equal to 746 Watts nearly.

Energy.—Work done in lifting a body can be restored on letting the body down again through suitable mechanism; the body lifted possesses, in its elevated position, a **stored-up Power of doing Work.** This power of doing work is called Energy. Again, a rifle-bullet, if it be caught by appropriate mechanism, has, **in virtue of its motion,** a power of doing work through that mechanism; and it also, therefore, possesses Energy. Energy of the former type, stored-up Energy, associated with Displacement, is called **Potential Energy**; energy of the latter type, Energy associated with Motion, is called **Kinetic Energy.**

A body or a system of bodies possessing Potential Energy is in a condition of **stress**: **work** must be done upon it in order to give it this condition of stress; when so stressed a body continuously **tends to move** —or the component parts of a system of bodies always tend to move—so as to get rid of the potential energy in the shortest time and by the shortest path. Thus a body on a height always tends to fall, vertically if it can. The Potential Energy which a body placed at a height gives up when it falls to a lower position is exactly **equal to the Work** which would have to be done in order to raise it from the lower position to the higher.

Example.—A rock weighing 1000 kilogr. falls 100 metres: what Potential Energy does it sacrifice? This is the Weight

(= (1000,000 × 981) dynes) × the Height (= 10000 cm.) = 9,810000,000000 ergs.

On a smaller scale, the **molecules** or particles of a body may have **work** done on them in order to effect relative **displacement** of them, and may tend in an analogous way to restore that work at the first opportunity, and resume their former relation to one another.

A coiled or stretched **spring**, a quantity of **compressed air** in an air gun, the **bent bow** of an archer, all possess Potential Energy and can do Work.

The Kinetic Energy of a moving body is (in ergs) equal to $\frac{1}{2}mv^2$, where m is the Mass (in grammes), and v is the Velocity (in cms.-per-second).

Example.—If a rock weighing 1000 kilogrs., falling freely from a height, reach the ground with a velocity of 4429 cms.-per-second, what is its Kinetic Energy just before touching ground? It is $\frac{1}{2}mv^2 = \frac{1}{2} \times 1000000$ grammes $\times (4429)^2 =$ 9,810000,000000 ergs.

Since the Kinetic Energy depends on the *square* of the Velocity, a projectile moving with doubled velocity can bury itself four times as deeply in earth as one of the same weight moving with single velocity: it then does four times the Work.

Kinetic Energy depends only on the actual Velocity, and on the Mass: and it does not depend on gravitation or on the direction of motion.

The Kinetic Energy which a falling body acquires through falling down is equal to the Potential Energy which it sacrifices during its fall; so that the **energy** is **not** lost or **destroyed**; it has only changed its form and become kinetic instead of potential.

Example.—In order that an object may, on falling freely, acquire a velocity of 4429 cm.-per-sec., it must (by equation 3 of p. 11) fall through a height of 10000 cm. This connects the last two examples, and shows that they refer to the same falling rock, and that the potential energy at the height is equal to the kinetic at the end of the fall.

At each and every intermediate point during the fall of an object, the sum of the potential energy not yet lost, and that of the kinetic energy already acquired, is equal either to the original potential energy or to the final kinetic energy.

When the body strikes the ground its motion is arrested: it no longer possesses kinetic energy: but still the Energy has not disappeared: it has assumed other forms; it has become converted into **Heat**, into the energy of a flash of **Light**, or into that of **Sound**; and the sum of these **different forms of energy** remains equal to the quantity of Potential Energy sacrificed by the falling stone.

A man ascending a staircase gains potential energy: but in his doing this, his muscles do work, and according to Hirn his body is perceptibly **cooler** for a moment, that is, until the excitement of the circulation causes him to become warm again, which occurs almost immediately. When he descends he sacrifices potential energy, and according to Hirn this has a perceptible effect in warming his body: the potential energy lost has reappeared in the form of **Heat**.

When a **plant** is shone upon by the sun, or the light of day, it absorbs Energy in the form of **Light** and **Radiant Heat**: part of this energy it expends, by means of its chlorophyll, in breaking up carbonic acid and forming less highly oxidised substances; and that energy will be restored when these substances are again completely oxidised, as when they are burned by fire, or by the slower process of oxidation which takes place on putrefaction, or within some animal which has fed upon the plant.

Energy is thus capable of assuming different forms, but it cannot be destroyed: and this is the doctrine of the **Conservation of Energy**.

It may assume, and always tends to assume, a form which may be of no use to us; namely, that of **uniformly distributed Heat**. In the working of a steam-engine a great deal of the potential energy which is liberated when the particles of the coal combine with the oxygen of the air is, as we say, wasted and lost, by escape of Heat to the condenser, by heating the air, and so on. We cannot recover that waste Heat and, as it were, it slips from our grasp: but though it has become useless to us it is not destroyed; it still exists somewhere, warming the Universe at large.

When a railway train has the brakes put on, and the train is being brought to a stand-still, the train is losing its Kinetic Energy: that kinetic energy becomes converted into Heat, and is presently dissipated as the brake cools down: but the Heat is not destroyed, though we cannot recover it again.

In every phenomenon with which we are acquainted there is some transformation of Energy into this relatively useless form; and this is the doctrine of the **Dissipation of Energy.**

Rotation

A body may be caused to rotate round a **point within** its own substance, as the bar in Fig. 25 rotates round the point O; or it may rotate round a **point outside** its own substance. In Fig. 26 the rod AB has moved into the position A′B′ by rotation round the external point O, which is similarly situated with respect to both AB and A′B′.

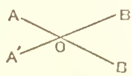


Fig. 25.

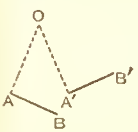


Fig. 26.

More generally, a body rotates round some **axis**, either passing through its own substance or not; and rotations may be **compounded**, as in the movements of the **eyeball** under the action of the different muscles, each of which tends to rotate it round a particular axis. If there be, as there is in the case of the eyeball, a single point through which all these axes pass, that point is called the **centre of rotation.** The result of the composition of rotations round different axes is a single rotation round a **resultant axis.**

The rotational analogue of Translational Displacement along a linear path is **Angular Displacement.** In Figs. 25 and 26 the rod has turned through an angle AOA′, and this angle is the measure of the Angular Displacement.

Angular displacements are measured in radians, Fig. 5. A complete rotation round 360° is a rotation through 6·2832 radians.

The analogue of Linear Velocity is **Angular Velocity,** measured in radians-per-second; and the analogue of Linear Acceleration is **Angular Acceleration,** radians-per-sec. per second.

The rotational analogue of Mass in translational kinetics is a quantity called the **Moment of Inertia.** For a single particle rotating round an outside axis or centre of rotation, this is mr^2, where m is the Mass (in grammes) and r the Distance of the particle from that centre. For a solid body it is the sum of all the (mr^2)'s of all the particles: and it needs mathematical calculation to find what this sum is in particular cases. But this sum is **always definite,** whatever the form of the body and wherever the axis of rotation may be.

Suppose we took a given mass, say a disc, and spread it out into a thinner disc, so that while the mass m remained the same, we increased the average value of r, the distance from the centre of rotation: by doing this we would increase the Moment of Inertia; and from the rotational point of view this would be equivalent to making it more massive, through making it more **unwieldy,** more difficult to rotate.

A singular example of this is furnished by the movements of a **cat** while **falling.** As is well known, a cat always lands on her feet if she have sufficient space in which to turn before reaching the ground. When she falls, back downwards, she brings her forepaws close to her ears and spreads her hind legs apart: she thus renders her hindquarters unwieldy: then she gives her vertebral column a twist: in consequence of this, her forequarters rotate in one direction and her hindquarters in the opposite direction; but the hindquarters, being relatively unwieldy, do not rotate as much as the forequarters do, and the forepaws are turned into a position beneath the animal. Then she spreads out her forepaws, thus making her forequarters unwieldy, while she brings her hindquarters together, stretching her legs out behind her; she now gives her vertebral column an opposite twist: the result is that while the now more unwieldy forequarters rotate comparatively little, the hind-legs are rotated into position. Now all the legs are under the animal, and she lands on her feet.

The analogue of Linear Momentum is **Angular Momentum**, the product of the moment of inertia into the angular velocity. This, like linear momentum, tends to remain uniform, except in so far as the motion is retarded by Friction.

Hence if **whirling water** be brought from a circumference towards the centre, as the water approaches the centre the radius diminishes, and therefore the Moment of Inertia also diminishes; but since the Angular Momentum remains the same, the Angular Velocity must increase; the water therefore whirls more rapidly. This may be seen in a **toilet basin** while emptying itself after the withdrawal of a central plug.

In Rotational Mechanics the analogue of Force is **Torque** or **Moment**. Let the force F be applied at A, and let the point round which rotation can be effected be O; the Torque or Moment, tending to produce rotation round O, is the product $F \times AO$, where F is measured in dynes and AO in cm.; *i.e.*, the Torque = the **force** × the **distance** from the point of rotation.

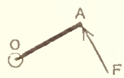


Fig. 27.

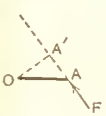


Fig 28.

If the direction FA be not at right angles to the line OA, the Torque is the product of the **force** F into OA′, the **shortest distance** between O and the line FAA′ (Fig. 28).

If the Force be **constant in direction**, this product will **diminish** in amount as the body turns from the position OA to the position OE. At A it is $F \times OA$; at B it is $F \times Ob$; at C it is $F \times Oc$; at E it is nothing. Hence, for example, the **forearm** moves with the greatest readiness at the middle of flexion. In order to maintain a maximum turning power, the force applied must be kept changing in direction, so as to be always at right angles to the bar turned, or to the shortest line between the point moved and the centre round which it is moved.

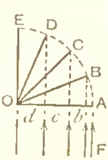


Fig. 29.

As a Force is the product of the Mass into the Acceleration, so a Torque is the product of the Moment of Inertia into the Angular Acceleration.

If there be no Translation accompanying the rotation, the **reaction** or **pressure** at the point or hinge O must be **equal and opposite** to the force F, Fig. 30, but it is **not in the same straight line** with it.

Fig. 30.

Examples. —The **triceps** muscle pulls the olecranon process back at the elbow-joint; the weight of the **head** causes the head to nod backwards or forwards, as the case may be, on a transverse axis at the occipito-atlantoid joint.

Two equal and parallel oppositely-directed forces, not in the same line, form a **couple**, as in Fig. 30. The **torque of a couple** is the *product* of either Force F (in dynes) into the Distance AO (in cms.) between the points of application of the two Forces which make up the Couple.

This Torque is the same round whatever point it may be taken; but the Moment of Inertia of the body acted upon is not the same with regard to all axes of rotation; therefore the other term of the product which measures the Torque, namely, the Angular Acceleration, is not the same when the body is pivoted on different points. The least moment of inertia, the least unwieldiness, is that round the **centre of mass**; and a body acted upon by a couple tends to rotate, of its own accord, round its centre of mass. But round that centre of mass it tends of its own accord, once it is set a-spinning, to rotate round the particular axis which presents the greatest unwieldiness, so as to send the bulk of the mass out to the greatest distance possible. Thus the earth rotates round its shortest axis.

To produce rotation a couple is necessary; but one of the terms of the couple may be the Reaction or Pressure on the hinge or axis of rotation. To prevent rotation a second Couple is necessary. In the **lever of the first order**, Fig. 31, a weight 12 at A tends to produce rotation round the **fulcrum** at F; the Couple consists of the downward Weight 12 at A and the upward Resistance, 12, of the

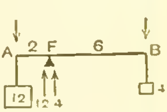


Fig. 31.

fulcrum at F. Opposed to this is another Couple, 4 at B and 4 at the fulcrum. Together, the upward **reaction** of the fulcrum is 16, and the Pressure upon the fulcrum is 16. If the **moments** of the two couples, the opposed Torques, be numerically **equal** there will be **no rotation**: the lever is balanced when A F : B F : : 4 : 12, so that the product $12 \times AF =$ the product $4 \times BF$.

If we invert the figure and suppose a heavy mass, say 16 kgr., at F to be borne on a stick by **two porters** at A and B, we see that the porter at A has to carry 12 kgr. while the porter at B has to bear the weight of only 4 kgr.

When the Forces applied and the Lengths of the arms are adjusted so that the Moments round F are equal, the lever is balanced. Any **excess** in either of the forces applied will then overcome the other force applied. When movement occurs, the **work** done by the one weight in descending is **equal** to that done in pulling up the weight lifted.

The **common balance** is a lever of the order just described. It lies even when the Moments on both sides of the suspension are the same. For this, if the effective arms be equal, the Masses counterpoised must be equal. If they be not, the apparent weight of the body weighed will be erroneous.

For example, let the one arm be 20 cm. in length and the other 20·1 cm. If 20 grammes be put at the end of the 20 cm. arm, the moment is 400 grm.-cm.; to produce an equal moment in the other arm, the mass put in the scale will be $\frac{400}{20 \cdot 1} = 19 \cdot 9$ grammes.

The Principle of Moments is illustrated by several forms of **Levers**, which are classified in three orders:

I. Fulcrum between the Force applied and the Resistance overcome. A crowbar, a handspike, ordinary pliers or forceps, scissors or shears, a poker, a dentist's lever, an American clothes peg.

II. Resistance between Fulcrum and Force: nutcrackers, oar of a boat (water practically fixed while the boat is pushed along), claw-hammer used for extracting nails, wheelbarrow.

III. Force between Fulcrum and Resistance: dissecting forceps, sugar-tongs, coal-tongs, the bones of the body. The muscles must act on a point of the bone fairly near the joint, else they would not pack within the skin: and they have accordingly to exert a greater pull upon the bone than the long arm of the lever can effect. Thus the contraction of the biceps could, if applied directly, lift about six times the weight that can be lifted in the palm of the hand: but the hand has a compensating range of movement.

Wheel and Axle.—A form of continuous lever in which again the moments round the axis of rotation must be equal if the instrument is to stand at rest, and one of the moments must be somewhat greater than the other in order to induce rotation. In the **capstan** and the **winch** the principle is the same. In the **bell-crank**, Fig. 33, the moments of the force A and that of the resistance B, round the hinge O, will be equal when the crank is in equilibrium; and the one will be a little greater than the other when the crank is in movement.

Fig. 32.

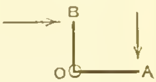


Fig. 33.

In all these cases the ratio between the Force exerted and the Resistance overcome is the inverse of the ratio between their respective Distances from the fixed point or fulcrum round which rotation takes place, or tends to take place.

In many cases mechanical power is not the desideratum, but **amplitude of movement**: for example, in the **sphygmograph**, in which the long arm of a lever of the first order has a writing-point at its tip and is used to record the movements of the pulse, which actuate the short arm. The **pen** as used in writing is a lever of the third order, and the point of the pen moves more than the fingers do. **Ross's lever** for measuring the thickness of microscopic cover-glasses is a lever of the third order, beneath which the cover-glass is inserted near the joint or fulcrum, and the amount of displacement at the distant end of the lever is measured on a scale.

As the kinetic energy of a body moving linearly is $\frac{1}{2}mv^2$, so the **kinetic energy** of a rotating body is half the Moment of Inertia into the *square* of the Angular Velocity. A **flywheel** in motion thus has Kinetic Energy, with some of which it parts when the machinery tends to slacken, and which increases in amount when the machinery tends to race: the flywheel thus acts as a store or **reservoir** of Energy, and tends to equalise the speed of running of the machinery.

Rotations and Translations can be **compounded** with one another; and the most general change of position of a body can be **resolved** into one translation and one rotation.

Deformations or Strains

When a body is deformed, its **particles** undergo **relative displacement**.

The principal forms of Deformation are **Shrinkage** or **Dilatation**, **Lengthening** or **Shortening**, **Shear**, and **Twist**.

In **Shrinkage** or **Dilatation**, and in **Shortening** or **Lengthening**, the particles of the body are crowded together, or else the intervals between them become larger.

Shear is shown by Fig. 34, in which successive layers of the substance slip over one another like the leaves of a book pressed out of shape.

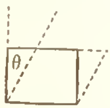


Fig. 34.

In **Twist** or **Torsion**, one end of a bar is made to rotate while the other is fixed: intermediate layers rotate through angles proportional to their distances from the fixed end.

If a body after being deformed or strained endeavour to resume its original form or dimensions, it is said to be **elastic**. An elastic body will, if deformed and left to itself, **oscillate** or **vibrate**; and we shall next consider Oscillations and Vibrations, beginning with those of a single **particle**, or of a small body which may represent a particle.

Oscillations and Vibrations

If we have a very **long pendulum**, a small bob, say a bullet, suspended by a cord, say a dozen feet long, and if we set this oscillating through a very **small arc**, say an inch or so, the path traversed is so **nearly a straight line** that we may assume it is a straight line. We observe: (1) successive swings are accomplished in **equal times**; (2) the bob travels to **equal distances** on each side of the midpoint or point of rest; (3) as it passes the **midpoint** the bob travels **most rapidly**, and gradually slows off as it nears the end of its swing. Two swings, one back and one fore, make a complete **oscillation**. The time taken to effect two swings, or one complete oscillation, is the **Period** of the oscillation: and the period of a seconds pendulum (eight-day clock) is **two** seconds. The number of oscillations per second is the **Frequency** of the oscillation; thus the frequency of oscillation of a seconds pendulum is $\frac{1}{2}$. The distance between the midpoint and either of the extreme positions (not the distance between the extreme positions) is the **Amplitude** of the oscillation: thus, if the whole path of the bob cover a distance of 1 inch, the amplitude is $\frac{1}{2}$ inch.

Motion of this kind, if in a **straight line**, is called **Simple Harmonic Motion**, and it may be rendered more intelligible by the use of what is called a **circle of reference**, as in Fig. 35. Assume a particle situated at the point A to start on a journey in a circle round O, and assume that its speed in that journey is **uniform**. Let it, in equal periods of time, reach the successive points *b*, *c*, *o*, *e*, *f*, *g* and H, and so on. From these points draw lines perpendicular to the line AH; we thus find the points ABCDOEFGH. These are the points reached, in successive equal intervals of time, by a particle moving along the line AH in Simple Harmonic Motion: and on the way back it reaches, again in equal intervals of time, the points GFEODCBA. A complete **oscillation**, once back-and-fore, thus corresponds to **one** complete journey round the Circle of Reference. Inspection of the figure shows us that near the middle of the course the spaces traversed in given intervals of time are greater than they are towards the end of the course: that is, the particle is moving with the **greatest velocity** at the instant when it is passing the **midpoint**. When it has passed

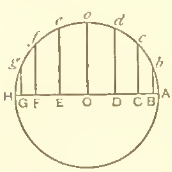


Fig. 35.

the midpoint it continuously slows down: it is subject to a Retarding or negative Acceleration; and it can be shown that the corresponding **retarding force** is, at any and every point of the path, **proportional to the displacement**, that is, to the distance between the moving particle and the midpoint O. The force tending to bring the particle back to O thus increases as the distance from O increases: when the particle is at H or at A this force is at its maximum: when the particle is at O there is no force pulling it towards O, but the particle has **momentum** and overshoots the mark; its **kinetic energy** is gradually transformed into **potential** energy as the particle recedes from O.

In every case where the Force tending to bring a particle back to O is thus proportional to the Distance of that particle from O, the particle will describe Simple Harmonic Motion: and if the particle take a certain time to oscillate in simple harmonic motion with a narrow range of amplitude, it will take exactly the same time to oscillate with greater amplitude, provided the amplitude is not too great. Simple Harmonic Motion occurs in **elastic bodies** when they **vibrate** after being deformed; and this principle underlies the phenomena of **sound**, of **light**, of **radiant heat**, and of some parts of the science of **electricity**.

We may **compound** Simple Harmonic Motions. To illustrate this let us fit up a **Blackburn's pendulum**, as shown in Fig. 36. A cord of sufficient length is passed through two holes in the horizontal cross-bar and also through a peg P, which may be turned so as to pull in or let out more or less cord. Both ends are then passed through a ring R, which may be slipped up or down, and they are connected with a heavy bob B, which contains some sand. The bob drops this sand as it travels, and

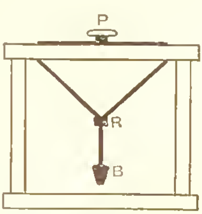


Fig. 36.

thus leaves its trail. If the bob B be moved parallel to the cross-bar and let go, it will swing from R as a centre: if B be moved at right angles to the cross-bar and let go, the whole will swing from the cross-bar; but if the bob be pulled obliquely and let go, both these motions will go on at the same time. Though adjusting by means of the peg P and the ring R we may give the two motions, which are at right angles to one another, any desired **ratio of frequencies**; and we may study the forms of the corresponding lines of sand. If the ratio be exactly as 1 to 2, that is, if the one oscillation be twice as frequent as the other, the trail is of a form such as is shown in Fig. 37. If A be the starting-point, once up and down this curve corresponds to once vertically up and down, and twice from right to left and back. In this case the curve is a **parabola**. With other ratios the figures are different; and they present a series of beautiful curves.

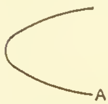


Fig. 37.

If the ratio be not exactly as 1 is to 2, the bob does not trace and retrace its track, but covers the baseboard with sand. The track gradually changes its form, and goes through a series of modifications; but the curve regains its original form when one of the oscillations has gained one complete period on the other. Thus if the ratio be 100 : 201, the curve will regain its form when the slower oscillation has been effected 100 times. If the ratio be 101 : 200 it will do so when the slower oscillation has been effected 101 times.

Suppose that we take a pendulum, free swinging and free to swing in any direction, and that we displace its bob say to the east: hold it there: then throw the bob to the north, and watch what happens. The bob moves in an **ellipse**, and may by a little management be made to move in the particular form of ellipse known as a **circle**. If it move in an ellipse, it moves more widely north-and-south than it does east-and-west, or else *vice versâ*: if its motion be circular, its north-and-south movement is equal to its east-and-west movement. But, observe, in the case of the circular movement, that when the bob is say at the point E, it is at the **middle** of its north-and-south movement when it is at the **end** of its east-and-west movement. As regards east-and-west, it is on the turn: as regards north-and-south, it is still in full swing. The latter movement is therefore $\frac{1}{4}$ **period in arrear** of the former. **Circular** movement is the result of the **composition** of two **equal** Simple Harmonic Motions which are **at right angles** to one another, and which **differ by** $\frac{1}{4}$ **period** in their stage of progress or their "**phase.**"

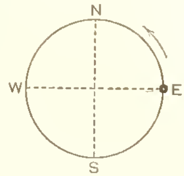


Fig. 38.

Suppose a body is moving in a Circle, and that we could **cut out** one of the two simple harmonic motions (S.H.M.'s) which make up its circular motion, we ought to have the other S.H.M. left. This we can actually accomplish. Suppose we have a wheel uniformly rotating, and that on this wheel there is a peg: this peg runs in a transverse slot in a frame which runs in guides. As the wheel rotates uniformly the frame will travel up and down: and it will execute a S.H.M. Conversely, if we could work the frame in S.H.M., we would make the wheel go round uniformly: and the **piston and crank**, acting on a steam-engine driving-wheel, form a sort of an approximation to this ideal.

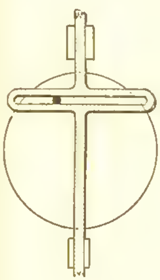


Fig. 39.

A Simple Harmonic Motion in a line AB may be **resolved** into two S.H.M.'s at right angles to one another. The line OB is the diagonal of the parallelogram YX; and OX, OY represent the respective amplitudes of the oscillations in the lines XX′ and YY′. If by any means the S.H.M. in the

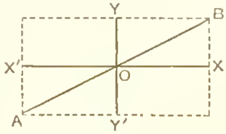


Fig. 40.

line AB were so hampered that no motion could occur in the line X′X or parallel to it, the S.H.M. in the line YY′ would not be interfered with, and would remain; but the rest of the movement would be extinguished.

If we carry a swinging pendulum through the air at a uniform rate in a direction at right angles to the direction of its oscillations, the actual path of the bob will be a **wavy line**. If the pendulum be carried slowly the path will be as in Fig. 41; if it be carried rapidly, the path will open out into a less wavy line (Fig. 42). We may make a pendulum draw this kind of line for us if it be provided with a sand-dropper or a writing-point, not by moving the pendulum itself, but by drawing a piece of paper at a uniform rate under the bob. In the same way a sounding **tuning-fork**, with a little writing-point attached to one of its prongs, will write on smoked glass, drawn past the tip of the writing-point, a wavy line like Figs. 41 or 42, according to the speed with which the smoked glass is made to run. And this not only shows that the tuning-fork is in a state of Vibration, but also enables us to find the **number of oscillations** it makes per second, by counting the number of alternations in the wavy line which is described during a known time.

Fig. 41.

Fig. 42.

The curved line thus drawn is the "**Harmonic Curve**," or "**Curve of Sines**." It is also called the **Simple Vibrational Curve**: and it presents itself in all parts of the study of vibrations or oscillations.

Waves.—If we have a very long **string**, of which one end is attached at a distant point, say to an opposite wall, and if we give it a few rapid jerks up-and-down at the free end, we see **waves** of **transverse vibration** running along the string. If the string be thin and flexible, the waves have exactly the outline of the Harmonic Curve. Let us draw one of these waves, from A to B (Fig. 43). The **slope** at A and B, and at the intermediate point C, is steeper than it is elsewhere; and the slope gradually falls off as we come from A to D, or from B to E, so that at D and E there is no slope. The **wave-form** is repeated behind A and in front of B. The points D and E are farthest from their original positions *d* and *e*: and the distance D*d*, or the distance E*e*, is the **Amplitude** of the oscillation. Any given **point** in the string executes a **simple harmonic motion** across the original line of the string; and the **wave-form travels** along the string. Observe that it is only a form or shape that travels along the string: each particle simply oscillates in the immediate neighbourhood of its original position.

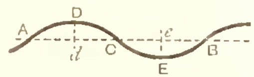


Fig. 43.

The distance between the two similar points A and B is called the **Wave-Length**: and on the analogy of waves of the sea, if the point D be called the **crest** of the wave, E is called its **trough**.

If the wave travel with a velocity v cm.-per-sec., and if the wave-length be λ cm., n waves will pass any given point per second; the equation which gives the relation between these is $v = n\lambda$.

Suppose further that in a string, along which a wave-form travels in this way, **another wave-form** had been induced by some means to travel **simultaneously** with the former. Let the two wave-forms for one complete wave be represented by the curves *a* and *b* (Fig. 44); then in order to find what happens we have, for every point such as *f*, to **add together** the displacements in the curves *a* and *b*: we thus find a series of points such as F, which together make a new curve *c*, and this again is a **harmonic curve**. If the two curves are **opposed** in their phase, the curve *c* corresponds

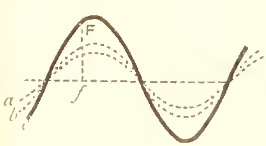


Fig. 44.

to the **differences** between them ; and if the two waves be of equal amplitude and opposed in phase, the result will be **rest**. Two waves may thus neutralise one another.

The same principle of addition of the displacements, for each point of the string, may be carried out to any extent. Suppose we have five waves running along the string, with periods which are in the proportions 1 : 2 : 3 : 4 : 5, so that the same length of string which contains five of the most rapidly recurring waves contains one of the slowest, two of the next, and so on. On adding the displacements for each point we find, as one result, that the string assumes a form which is apparently most complex,

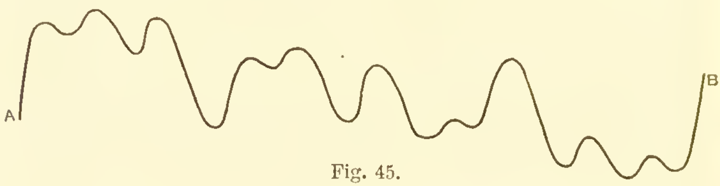


Fig. 45.

but which is the same both erect and upside down, and which also recurs in front of B as well as behind A.

This form, since it recurs at equal intervals of time, is said to be "**periodic**"; and "**Fourier's Theorem**" is that **any** vibrational motion or form whatever, provided that it be periodic, can be **resolved** into **simple** oscillations or waves, which occur simultaneously, and whose **frequencies** bear a **simple numerical relation** to one another.

In some cases we have, instead of transversal vibrations, **Longitudinal Vibrations**. In these the particles, say of a rod, are not displaced transversely, but back-and-fore along the direction of the rod. Here again the **harmonic curve** comes in, not as showing the form assumed by the rod, but as showing the Amount of Displacement undergone by each particle of it. In Fig. 46 if the rod AB be in longitudinal vibration, of which one wave-length only is shown, and if upward portions of the curve indicate displacements forwards while downward portions of it indicate displacements backwards, the amounts of displacements would be measured by

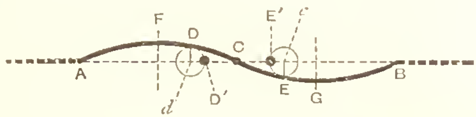


Fig. 46.

such lines as dD, eE, and the real positions of the particles originally at d and e would be at D′, E′. Hence the particles of the rod are **crowded together** towards C and **separated** away from A and from B, and there are thus **alternate** points of maximum Compression and maximum Rarefaction. The particles originally at F and G have undergone **maximum displacements**; but the particles originally at these points have, in their new positions, undergone no separation from or approximation towards one another.

In a **membrane** which is uniform in all directions, the waves from a point of disturbance are mostly transverse to the surface, and run from that point in concentric **circles**. The front of the wave is thus always circular in form, and the Direction of Propagation of the wave is at **right angles** to the **wave-front.**

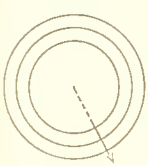


Fig. 47.

In a **tridimensional** substance, if that substance be similar in all directions, the waves from a point of disturbance travel in concentric **spheres**; and the direction of propagation of the wave is again always at right angles to the wave-front. **Each point** in the wave-front acts as the **centre** of a new disturbance; and the aggregate effect is the formation of a continuously propagated Wave-Front.

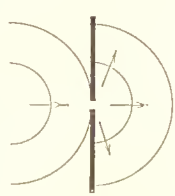


Fig. 48.

When a broad Wave-Front meets an **aperture** there are three cases: (1) Fig. 48, the wave-length is **great** in comparison with the aperture, in which case the Aperture itself acts as a Centre of Disturbance, from which a wave-motion **spreads**; (2) Fig. 49, the wave-length is very **small** in comparison with the aperture, in which case the wave is continued only within the limits imposed by the aperture, as shown by the figure, and **does not spread** laterally; (3) intermediate conditions, in which there is some spreading of the wave-front beyond the limits indicated by Fig. 49.

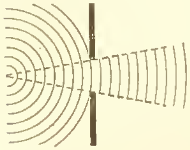


Fig. 49.

If a wave-front, limited as in Fig. 49, be **concave** as in Fig. 50, it will first bear down on a point F, and then, after passing through that point, will diverge from that point as from a centre. Such a point is called a **Focus**.

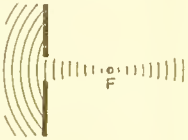


Fig. 50.

If we attend to the **directions** in which the **wave-front** is **propagated,** we may make diagrams to represent these directions in the cases of Figs. 49 and 50. These diagrams are shown in Fig. 51. The **lines** which represent the **directions** of propagation of the wave-front are called **Rays.** It is in many ways more convenient to study the relations of these rays than it is to follow up the Wave-Front itself: but the use of this device implies that the Wave-Length is **very short** in comparison with the actual breadth of the wave-front.

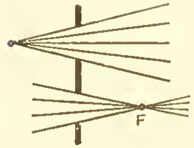


Fig. 51.

Reflexion of Waves.—When waves impinge upon a smooth surface, the wave-motion may be reflected or turned back. If a wave diverge from a point O before striking, it diverges after reflexion *as if* it had come from a point I. Each ray is reflected in such a way that the "**angle of inci-**

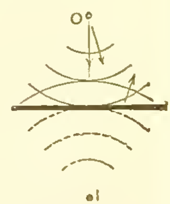


Fig. 52.

dence" i is equal to the "**angle of reflexion**" r (Fig. 53).

If a Plane Wave-Front (one in which the "rays" are parallel to one another) meet a **parabolic mirror** placed squarely opposite to it, the rays, after reflexion, all converge upon and pass through a single point F, from which they afterwards diverge as from a single centre; and conversely, if the waves at first radiate from F they will, as they recede from the mirror, present parallel rays and a plane wave-front (Fig. 54).

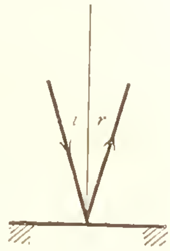


Fig. 53.

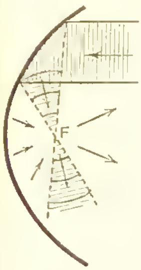


Fig. 54.

If the same plane wave-front encounter a **spherical mirror**, the result is approximately but not exactly the same. The rays reflected from the outer part of the mirror cross one another too near the mirror; but those very near the axis of the mirror cross one another in the immediate neighbourhood of a point F, which is half way between the surface and the centre of curvature, C, of the mirror. From this two consequences follow: (1) there is **no true focus** for all the rays; (2) there is a double curved line called a **caustic**, Fig. 56, along which all the foci for all the rays lie. Along this Caustic the reflected wave-motion will be most energetic, and will be most **concentrated** at or near the tip F; and the **tip** F of this Caustic is called the **Focus** of the Mirror. If we take a strip of bright metal, bend it into a curve, and hold it upon a piece of paper in front of the sun, we shall see the Caustic curve, produced by reflexion of the waves of sunlight upon the paper.

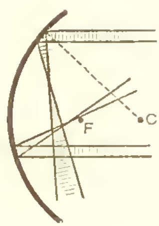


Fig. 55.

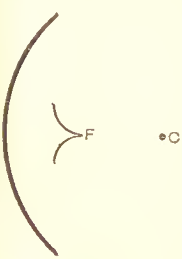


Fig. 56.

Refraction of Waves.—If a wave enter a medium in which it travels **more slowly**, one part of the wave-front may be **retarded** as it enters, and may swivel round before the rest of the wave-front has arrived. Fig. 57 (*a*) shows such a wave-front in the act of entering the hampering medium through a plane surface: Fig. 57 (*b*), shows the same wave-front after it has entered the medium. It is deviated from its former direction; it is "**refracted.**" In the same way a line of soldiers, walking obliquely into a heavy field, tends to turn its front.

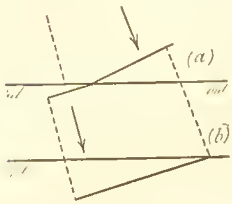


Fig. 57.

The relation between the **Angle of Incidence** i and the "**Angle of Refraction**" r is explained by Fig. 58. If the angle of incidence be i, from the point O where the ray strikes the glass we draw a circle, cutting the incident ray at I. To the line NN′, which is at right angles to the refracting surface, we draw In parallel to that surface; then we measure off a line Rn' which bears to In the same ratio as the **velocity of wave-propagation** in the second medium bears to that in the first; and, lastly, we contrive to find a direction for the line OR, which will enable Rn' to be fitted in, parallel to the refracting surface, in the way shown in the figure. OR is the direction of the refracted ray. The ratio (In÷Rn'), which is a number, is called the **Index of Refraction** of the second medium with respect to the first.

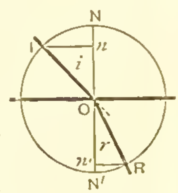


Fig. 58.

For each Angle of Incidence there is a corresponding Angle of Refraction: and when rays from a centre S strike a hampering medium they are severally so refracted that the whole wave-front (though really hyperboloidal in form) is **very nearly spherical** in form, with its centre S′ behind the source S, at a distance S′A = SA × the Index of Refraction: and the wave

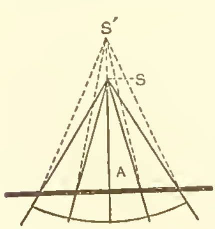


Fig. 59.

therefore travels in the second medium approximately *as if* it had come from the point S′.

When these refracted rays regain the original medium through a second surface, each of them **re-gains its original direction**, if the second surface be **parallel** to the first: but the rays are not all directed as if from the original point S; they travel as if from a caustic curve whose tip is at S. The emergent wave-front is not quite spherical.

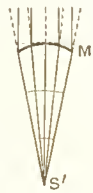


Fig. 60.

If a plane wave-front (parallel rays) strikes a **convex** spherical surface of the hampering medium, it is made to **converge**, approximately, towards a point S′, Fig. 60. If it strike a **concave** surface, it is made to **diverge**, approximately, *as if* from a point S′, Fig. 61. If we have a spherical wave made to pass in this way through two or more spherical surfaces of different media, there is **always some point** from which the emergent wave-front **seems** to diverge, or towards which it really does converge, as the case may be; in both cases **approximately** only. This is the principle of the action of **lenses** in Optics.

Fig. 61.

When a wave is refracted there is generally a part of its motion reflected at the same time: but whenever a **reflected** wave is produced **in a denser medium** at the bounding surface of the less dense medium, there is **loss of half a wave-length**, so that an impinging condensation is reflected as a rarefaction, and *vice versâ*.

Stationary Vibrations.—A cord may be set in transverse vibration between **fixed extremities**. It vibrates **as a whole**: and its **form** as it vibrates is that of half a wave as its upper limit of distortion, and the other half of a wave as its lower limit. The **frequency** of the oscillation is such that a wave of


Fig. 62.

the same frequency, running along a free string, would have a Wave Length equal to **twice the length** of the fixed string.

If the midpoint of the string be held fast, the string vibrates in two segments, oppositely distorted: and the Frequency is twice as great as at first. If a point one-third of the length from the end be held fixed, a point one-third of the length from the other end assumes a position of rest, and the string vibrates in three segments, oppositely distorted and pivoting round two stationary points.


Fig. 63.

A string may similarly be made to vibrate in 4, 5, etc., such oscillating segments or "**Loops**" equal in length, oppositely distorted, and pivoting round stationary points or "**Nodes**"; and the length of each loop is *half* the wave-length of the corresponding oscillation.


Fig. 64.

A **rod**, or a **string**, can vibrate **longitudinally.** If it be fixed at both ends it obeys the same laws as a string vibrating transversely: it can have Nodes and Loops in the same way: and the wave-lengths of the various undulations into which it may enter are $\frac{2}{1}$, $\frac{2}{2}$, $\frac{2}{3}$, $\frac{2}{4}$, $\frac{2}{5}$, etc., times the length of the rod.

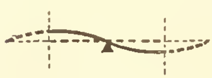


Fig. 65.

If it be free at both ends, with the centre fixed, the numerical ratios are again the same; but the rod lengthens and shortens at the free ends, so that each **free end** is always the **centre** of a **loop** (Fig. 65).

If it be fixed at one end only, it is as if we took half of Fig. 65; the wave-lengths of the respective longitudinal vibrations are $\frac{4}{1}$, $\frac{4}{3}$, $\frac{4}{5}$, $\frac{4}{7}$, etc., times the length of the rod; and as before, the free end of the rod is always the centre of a Loop: but no oscillation which would tend to set the fixed end in motion can be present: for which reason the 2nd, 4th, 6th, etc., vibrations are necessarily absent.


Fig. 66.

Interference of Waves takes place between waves from different sources. If in Fig. 67 we represent **crests** of waves crossing one another by dark lines, and the intervening **troughs** by dotted lines, we may mark by black circles the spots where crests coincide or concur with crests, or troughs with troughs, and by plain circles the spots where crests of the one wave-system are thwarted by the troughs belonging to the other. Where crest meets crest, or troughs troughs, there is a double amplitude: where crests meet troughs there is approximate quietude. We see that there are alternate lines of black circles and lines of plain ones. Along the former of these lines there is **double movement**: along the latter there is **approximate rest.** If we trace this out in a large diagram, we find that when two **points**, A and B, Fig. 68, act as sources of wave motion, there are alternating lines or **fringes** of alternate rest and motion at *a*, *b*, *c*, *d*, etc. The **smaller** the **wave-length**, the **nearer** to one another will the fringes be.

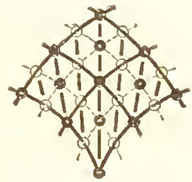


Fig. 67.

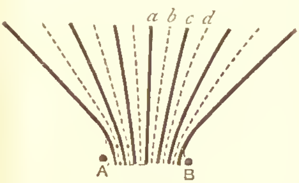


Fig. 68.

If we take a wave-front diverging from O and passing through an aperture AB: if the wave-lengths be **very small** in comparison with the breadth of AB, we shall find, on similar principles, that at a point P well **to one side** of the rays OA or OB, the **effect** of the wave-front is **nil**: for the different parts of the wave-front act as centres of disturbance, and as they are at different distances from P, the waves from these different centres, even if they had been formed, would interfere with one another so as to produce Rest at that point.

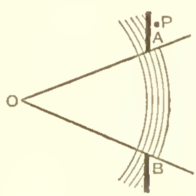


Fig. 69.

At the same time the points A and B act as centres producing waves, which in the case of Light interfere with the sharpness of outline of the bright disc formed on a screen beyond the aperture AB.

Diffraction-Grating.—If a plane wave-front strike a gridiron-structure, represented in section in Fig. 70, there will be waves transmitted directly through; but there may also be waves sent in other directions, as shown.

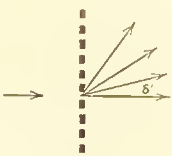


Fig. 70.

These directions make certain angles δ', δ'', δ''' with the original direction of propagation: and these angles are such that $\sin \delta' = n\lambda$, $\sin \delta'' = 2n\lambda$, $\sin \delta''' = 3n\lambda$, etc., where n is the number (integral or fractional) of grids per cm., and λ is the wave-length in cms. There is no angle whose sine is greater than 1; and hence if any of the products $n\lambda$, $2n\lambda$, $3n\lambda$, etc., be greater than 1, the corresponding deflected waves are not formed at all: for example, in the figure, as drawn, there cannot be a fourth such direction.

The **energy** of Vibration and Wave Motion is **equally** divided between the **kinetic** and the **potential** forms; and it is proportional to the *square* of the Amplitude.

CHAPTER III

FRICTION

LET us rest a mass m (say 1000 grammes) on a board T, and let us endeavour, by pulling it by means of a spring-balance, to make it **slide** on the board. The spring is stretched out somewhat, and yet the block m is not moved. It will slide, but only when the spring-balance gives a certain reading; let this be, say, 600 grammes. This is $\frac{3}{5}$ of the 1000 grammes in m.

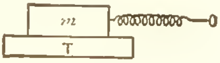


Fig. 71.

The Coefficient $\frac{3}{5}$, as found by this experiment, is the **Coefficient of Statical Friction** between the substance of which the mass m and that of which the table T consists.

The Total Pressure upon the table is 981,000 dynes; the pull on the spring is 981×600 dynes: the latter is $\frac{3}{5}$ the former. Generally, the Pull on the spring which is required to **start sliding** movement is equal (in dynes) to the *product* of the Coefficient of Statical Friction into the Total Pressure (in dynes) between m and T.

Let us **squeeze** m against T, as, for example, by a screw table-clip which embraces both m and T; we thus increase the Total Pressure between m and T; the pulling force to be applied through the spring must still be equal to $\frac{3}{5}$ the increased pressure before there will be any sliding: and it must therefore be greater than before.

We may increase the Total Pressure in another way, namely, by **multiplying the surfaces.** Take two pamphlets: arrange them with their leaves alternately interplaced: the one can be pulled out of the other. If, however, a small weight be laid upon them they cannot be pulled asunder without a very great effort. The Total Pressure is practically multiplied by multiplying the number of surfaces on which the same pressure acts.

Let us **tilt up** the table T of Fig. 71 until the mass m just begins to slide. There will be no sliding until the **angle** BAC becomes such that the ratio $BC/AC = \frac{3}{5}$, ACB being a right angle. Upon the angle BAC depend the angles at which sand, heaps of grain, etc., can stand.

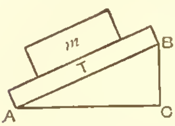


Fig. 72.

If m be pressed upon T by a stick, which is at first held vertical, and which is gradually inclined to the vertical, sliding begins when the stick is inclined to the vertical at an angle equal to the angle BAC.

Different substances have between them different Coefficients of Statical Friction: and even between the same substances the coefficient depends also upon the **condition** of the surfaces: it is greatly reduced by **lubrication**, and it is somewhat increased by keeping the surfaces in **contact** for a long time.

The Total Friction **does not depend** at all upon the **area** by which m rests on T; the pull upon the spring-balance must be the same in order to make m start, whether it rest on T by a large surface or by narrow runners only.

Friction is like a Force **preventing** sliding, and itself called into being by the effort to make the mass m slide; but this preventing force, or Frictional Resistance, cannot exceed a certain maximum. For example, Friction may prevent a **microscope tube** from sliding down by its own Weight merely, but we can overcome its resistance, and pull or push the tube up or down.

When a **rope** is tied round a **post**, it will not slip if it be held by a very slight force; and the security of **knots** and bandages depends very largely upon the Statical Friction, which holds in check their tendency to pull loose or to slip.

Next, let the experiment of Fig. 71 be continued by **keeping** the block m **sliding**: it will be found that the reading of the Spring-Balance is now materially **smaller**, say 400 grammes only. This is $\frac{2}{5}$ the weight of m; and thus we now have a new coefficient, the **Coefficient of Kinetical Friction.** It is thus easier to keep the mass m sliding than it is to start it.

Within wide limits the Coefficient of Kinetical Friction is the same—there will be the same tension on the spring-balance—**whatever the speed** may be; but if the speed be allowed to become very small, this coefficient tends to increase.

Kinetic Friction is like a Force, tending to **retard** the sliding when once this sliding has been started: and this Retarding Force is **constant**, whatever, within wide limits, may be the actual velocity of movement.

The arrest of the **foot** at each step is, when the walk is gliding, an example of kinetic friction.

This Retarding Force is, numerically, equal to the *product* of the Coefficient of Kinetic Friction into the Total Pressure between m and T.

In the case supposed, this coefficient is $\frac{2}{5}$, and the Pressure is the Weight of 1000 grammes = 981,000 dynes; whence the Retarding Force = 392,400 dynes.

This retarding Force acts, in the case supposed, on a mass of 1000 grammes; whence the retarding Acceleration (= retarding Force ÷ Mass) = 392·4 cm.-per-sec. per second. All problems of frictional retardation may be dealt with by using the ordinary equations for Accelerated Motion, p. 11, the value of the **frictional negative acceleration** being determined as just shown, and used in the formulæ.

The Pressure between the sliding surfaces may be produced by any means; and if it be increased, as by clamping down a **brake**, the retardation increases.

Example.—What must be the total pressure put on the brake in order to stop ($v_t = 0$) a train of 160,000 kilogrs. ($m =$

160,000000 grammes) running at 54 kiloms. an hour ($v_o = 1500$ cms.-per-sec.) within 1 kilometre ($s = 100,000$ cm.)? The Retarding Acceleration required, $-a$, must first be found. By equation (3), p. 11, $0 = \sqrt{(1500)^2 - 200000a}$, whence $a = 11 \cdot 25$ cm.-per-sec. per second. But in railway work there is always a frictional Retarding Force equal to, say, $\frac{1}{320}$ the Weight of the train; this Force is $\frac{1}{320} \times 981 \times 160,000000 = 490,500000$ dynes. There is, therefore, already a retarding or negative Acceleration of $\frac{490,500000}{160,000000} = 3 \cdot 065625$ cm./sec.^{2} What is wanted, then, is a **supplementary** negative Acceleration of 8·184375 cm.-per-sec. per second, or a retarding Force of $160,000000 \times 8 \cdot 184375 =$ 1309,500000 dynes. This Force is, as we have seen, also equal to the product of the Pressure into the Coefficient of Kinetic Friction between the rubbing surfaces of the brake. Say that between the wood and the iron this coefficient is $\frac{2}{5}$; then the pressure must be 3273,750000 dynes = the weight of 3,337156 grammes. If the rubbing area be small the pressure must be intense; if it were only 1 sq. cm. the pressure would have to be 3229 times the atmospheric pressure (which is 1,013663 dynes per sq. cm.): if 10 sq. cm., 322·9 atmospheres; if 1000 sq. cm., 3·229 atmos.; if 3229 sq. cm., 1 atmo. Observe carefully that the Pressure which has to be applied is the Total Pressure; and that the pressure which must be applied per sq. cm. will depend on the rubbing Area of the brake.

If a vehicle run down a **slope** (Fig. 73), such that AC/BC is equal to the Coefficient of Kinetical Friction, it will run at a **uniform velocity** without any propulsion; for the **negative** Acceleration due to Friction is then exactly **balanced** by the **positive** Acceleration due to Gravity, resolved in the direction AB.

Fig. 73.

The **work** done against Friction is the *product* of the frictional **resistance** or retarding Force into the **space** traversed. When an engine takes a train uphill, it has to do lifting work as well as work against friction; and if it go up from B to A, in Fig. 73, it has to do the work of lifting the weight of the train through the height CA *plus* that of overcoming the frictional resistance through a distance BA. The Energy expended in doing work against Friction is always converted into Heat.

Kinetic Friction thus always acts as if it were a retarding Force; but it does not exist unless and until there is an actual Velocity.

Of all forms of motion, **rolling** upon well-lubricated wheels is that which presents the **least** friction: in this case the coefficient of kinetical friction is much smaller than it is in the case of sliding.

At very high speeds or pressures the coefficient of friction may differ from what it is within ordinary limits. For low speeds thick oils make the best lubricants; for very high speeds, thin oils or water.

When **solids** move **in liquids** at low speeds the law is the same as when solids move upon solids; but at high speeds the Resistance itself tends to vary as the Velocity.

When **oscillatory movements** are subjected to Friction always proportioned to the Velocity, the oscillations are slower than they would have been in the absence of friction, and they continuously diminish in amplitude; but they will be executed always in equal times. If the frictional resistance be very great, there will be no oscillatory movement; and the distorted or displaced body will simply return slowly to its normal form or position.

CHAPTER IV

MATTER

The "**essential**" Properties of Matter are:—

(1) Definite **Quantity** or "**Mass**" in each object.
(2) **Indestructibility** of Matter, so far as we know.
(3) Definite Quantity of each Chemical **element.** The chemical elements cannot, as yet, be transformed into one another.
(4) Matter made up of **Molecules**, or small particles.
(5) These molecules mutually **non-interpenetrable.**

Hence Matter is said to be impenetrable; and if we have, for example, a "**penetrating wound**" of the body, the penetrating weapon has gone between molecules, not through them or into them.

The "**general**" properties of Matter are:—

(1) **Inertia.**
(2) **Weight** — the force of Gravitation upon Matter.
(3) **Divisibility** down to the molecular condition.
(4) **Porosity.**

The "**contingent**" properties of Matter are these which depend upon the particular kind of substance under consideration, such as Density, Colour, etc.

The "General" Properties of Matter

Inertia.—To say that matter is **inert**, or "has Inertia," is another way of saying that it will not move if at rest, nor cease moving if in motion, unless some **force** be applied to it. If it be in motion, in a given direction, it tends to continue in motion in the same direction; if it be rotating it tends to go on rotating in the same plane in space. In the case of a moving body, **friction** is considered as equivalent to a Force.

Examples.—It is difficult to set a **heavy gate** swinging on its hinges; when in motion, it is difficult to stop it. It is difficult to pull up a **railway train** or a heavy van promptly. A **rider** may be thrown forward off his horse, if the animal stop abruptly under him; his body continues to move forward. If a horse abruptly stop or fall in front of a **heavy waggon** or coach moving rapidly, the vehicle comes on and runs upon him. A **hare** abruptly moves out of her path, but the pursuing greyhound cannot at once stop or change his course and is carried past. When **dust** is shaken off a book, or **snow** is kicked off the shoes, the book or the shoes are set in rapid motion, and this rapid motion is abruptly stopped; but the dust or the snow flies onwards. **Water** in pipes, set a-flowing and then suddenly turned off, may pour on so as to produce, with a jerk, a great pressure within the pipes. **Mercury** used in tubes for measuring variable pressure will often run forward, once it is in motion, and give readings which are too high.

When a man stands at the stern of a **boat** or the back of a **car**, and the boat or the car suddenly moves forward, he may fall backwards. When a **carpet** is dusted by beating it, the carpet is suddenly propelled forward, but the dust remains. A bad rider may get his body jerked so as to throw the comparatively stationary mass of **blood** backwards against the valves of his veins. When a mass is suspended on a **spring balance**, and the balance is suddenly lifted, the spring will be unduly stretched, for the suspended mass does not at once participate in the movement.

A **hammock** in a ship tends to remain in the same place while the ship swings round it. A heavy **fly-wheel**, rotating, requires some force to make it turn the plane of its rotation.

Gravitation and Weight.—Every particle of Matter in the Universe is attracted directly towards every other particle with a Force varying *directly* as the **mass** of each particle, and *inversely* as the *square* of the **distance** between them. This proposition is called the "**Law of Gravitation.**"

The Force in question is called the **Force of Gravitation**; and the Force of Gravitation acting on any particular body, pulling or tending to pull it towards the Earth, is called the **Weight** of that body.

It is very singular that the Weight of a body depends only on its Mass and exactly on its mass, and not in the least upon the quality or kind of matter. If it were otherwise, different kinds of material would fall at different rates; but in a vacuum, where the friction of the air does not interfere with the fall of a falling body, a feather falls with precisely the same speed as a piece of lead; and a light body falls at the same rate as a heavy one. In the last case, though a smaller Force of gravitation acts on the lighter body, the Mass, or the quantity of matter in that lighter body, is smaller in exactly the same proportion; and the downward **acceleration is the same** in both.

We have used the number **981** as being the Acceleration (in cms.-per-sec. per second) due to Gravity acting on a falling body. This number is, however, not the same at all points of the earth's surface; it **varies** from 978·1028 at the Equator to an estimated value of 983·1084 at the Poles. The value 981 is intermediate between the Paris and the Greenwich values, which are respectively 980·94 and 981·17. At Edinburgh it is 981·54. A **spring balance** will therefore be slightly more distorted by the Weight of a given mass in Edinburgh than in London, more in London than in Paris, and so on.

At any one place the force of gravity appears to be constant; and gravity may be applied for the purpose of securing a **constant unvarying pull** say upon a spring (see Fig. 14). Tension produced by the spring itself might not have been so uniform, for the spring might weaken as time went on.

The Force of Gravity may be roughly **measured** by an **Atwood's machine.** In this two equal masses, say of $49\frac{1}{2}$ grammes each, are balanced over a pulley: then a mass, say of 1 gramme, is put upon one of these, and the whole masses begin to move. The whole mass moved is 100 grammes; the space traversed in one second is found to be 4·9 cm.; therefore (p. 11, equation 2) the acceleration is 9·8 cm.-per-sec. per second; whence the **Force** acting on the masses is (100 grammes × 9·8 cm./sec.^{2} =) 980 dynes; but this force acting is the **Weight** of one gramme. This is a very rough method: and the better method is by means of a **pendulum.** We measure the **length,** l cm., of the pendulum; and we also count the number of oscillations (to-and-fro) in a given time, and thus ascertain the **period** (t seconds) of each complete oscillation. Then the number 981, or whatever it may be, is equal to 39·4785 l/t^2.

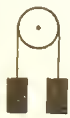


Fig. 74.

A **pendulum,** when pulled to one side, is restored to position by its **weight**; and as it oscillates, its kinetic energy always carrying it past the point of rest, its **period** of oscillation depends on its **length** and on the local Force of **gravity.** If the force of gravity be increased, the time of swing is shortened, for the force acting is greater: if the length of the pendulum be increased the time of swing is also increased, being proportional to the square root of the length of the pendulum, so that a pendulum one-fourth as long oscillates twice as fast.

The **true length** of a **pendulum** oscillating at a given rate is **measured** not by measuring the length of a simple pendulum consisting of a bob suspended on a cord, but by finding the distance between two points C and D (on opposite sides of the midpoint of the rod) on a solid rod or "**compound pendulum**" AB, such that the rod oscillates in equal times whether suspended on the one point or on the other. This can be effected to any nicety, and by taking a sufficient number of oscillations the period t can also be found exactly; whence by this method the Acceleration of gravity can be measured to any degree of accuracy desired, with the aid of the above formula.

Fig. 75.

In **walking,** the swing of the leg or arm tends to resemble that of a compound pendulum: but it is interfered with, being generally shortened, by muscular effort.

A pendulum oscillates in approximately **equal periods,** whether its arc of oscillation be great or small, so long as the angle through which it swings does not exceed some 2° or 3° at most

The motion of a pendulum is approximately **simple harmonic**; for so long as the pendulum is displaced only through a very small angle, the Force tending to bring the pendulum back is very nearly **proportional to the displacement.** This, it will be remembered, is the criterion of Harmonic Motion.

When gravity acts on a falling object, it acts as if it were concentrated at the **centre of mass** of that object. The centre of mass moves steadily, but the object as a whole may rotate round that centre of mass: and it may, especially if it have a bias (that is, if it be not uniform, so that the centre of mass does not coincide with the centre of figure), rotate and swerve round the centre of mass in a puzzling way. The Centre of Mass is also known as the **Centre of Gravity.**

The Centre of Gravity of a body always tends to assume the **lowest possible position.**

Hence if any body be freely suspended by a cord, a **vertical line** drawn from the point of suspension passes through the centre of gravity: and if we take more than one such point of suspension, we may find the point at which such vertical lines intersect. This is the Centre of Gravity of the body. Thus the centre of gravity of any plane figure may be found by cutting it out in cardboard of uniform thickness, suspending the cardboard figure from two different points, drawing the vertical lines passing through the respective points of support, and finding the point of intersection of these lines.

The **head** generally tends to rotate and fall forward on the chest; the **trunk** forward on the pelvis; the head, trunk, and thighs backwards round the knee joints; the whole body forward over the ankle joints. When a patient is **carried** there is a tendency for the body to sag downwards and for the head to rotate backwards: hence he should be properly supported.

In every case the Centre of Gravity must lie **over the base** of support, else the body will topple over.

When a man **stands**, the base of support is bounded by the heels, the balls of the great toes, and lines joining these; if he bear a **burden** the centre of gravity may not be brought over this base without his stooping; if he be very obese he may have to assume a very erect gait. Under normal conditions his centre of gravity is at a point about the front of his last lumbar vertebra. An old man broadens his base of support by the use of a staff.

Other illustrations are afforded by the sleeping of **quadrupeds** on their feet, by the **kangaroo** supporting itself with the aid of its tail, by the **waddling** walk of a person with a broad pelvis, by the **lateral bend** of the body when a burden is carried in one arm, and by the **erect attitude** assumed when burdens are carried on the head.

If an object have its Centre of Gravity relatively **high** or its base **narrow**, a slight displacement will bring the centre of gravity to a position in which a vertical line drawn from it falls **outside** the base of support: and then the object tends, unless propped up, or unless its base of support be moved up under it, to topple over.

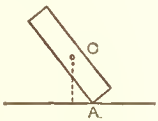


Fig. 76.

Examples of this are furnished by children and young animals learning to walk, or by persons moving or standing on a rope or wire, or stilts, or skates, or a narrow rail, or on one foot; and by boats in which people stand, high chairs in which children are seated, cars heavily loaded atop, or by deck-loaded ships. The bringing up the base of support to a position beneath the centre of gravity is illustrated by the forward step a person takes on reaching the ground when alighting from a tramway car.

If the Centre of Gravity of a body be in the **lowest** possible position, **work** must be done in disturbing it; for any displacement **lifts** the centre of gravity. In such a case the body is said to be in **stable equilibrium.**

This is illustrated by a ball lying in a bowl; when displaced it rolls back, and **oscillates** in the bowl until it comes to rest. The same thing is seen in a pendulum, a swing, a cradle, a rocking-horse, a ship well ballasted; in the last case the oscillations are somewhat like those of a pendulum whose point of suspension and whose length both vary.

The **most stable** equilibrium is ensured when the **greatest** amount of **work** has to be done **before overturning** can occur; and hence the base should be as **broad** as possible, so as to make it necessary to raise the

Centre of Gravity to the greatest height before upsetting the object; and the distribution of matter should be such as to make the **lowest** parts of the object the **heaviest**.

If a **microscope stand** be **narrow**, or not sufficiently weighted at the base, a slight disturbance may upset the instrument: for all the work it would be necessary to do would be to lift the centre of gravity C up to D by rotation round the point A along the arc CD. If, on the other hand, the base be **broad** and heavy, the lifting work is greater, and the object is not so readily upset. Many microscope stands have the foot light and narrow; and such instruments are easily overset laterally. When the stand is a **tripod**, it is virtually a triangular stand, and the instrument is somewhat more readily upset in the direction CE than in the direction CA. If the stand be broad, heavy, and **circular**, it is equally difficult to upset in all directions so long as the Centre of Gravity of the instrument is over its centre; but if the centre of gravity come to lie over some other point C, the instrument is most readily upset in the direction CE. For **steadiness** an instrument should stand on **three** points, because three points are sure to adapt themselves to the roughness or warp of any table, while four points on a surface may not do so; but these points should be no longer than is absolutely necessary, so that any tilt may cause the edge of the broad and heavy base to press upon the table.

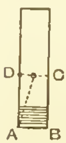


Fig. 77.

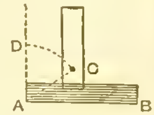


Fig. 78.

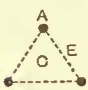


Fig. 79.

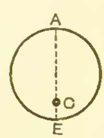


Fig. 80.

A **lamp-stand** should be either heavily loaded at its base, or else should be mounted on a very broad base; most of the large drawing-room floor lamp-stands are very dangerously designed, and should, if used at all, always be screwed to the floor.

A **photographic camera** supported on three legs may be rendered less easily overset by hanging a bag of stones from the three **tripod legs**: the centre of gravity is thus lowered.

When a body is poised so that its Centre of Gravity is in the **highest** possible position, it always **tends** to turn over so as to bring it to the lowest; but it may remain at Rest. When thus at rest it is said to be in **unstable equilibrium**; and the slightest displacement oversets it.

Where, as in the case of a uniform wooden sphere floating in water, the centre of gravity is neither raised nor lowered on the occurrence of a displacement, the Equilibrium is said to be **neutral.** **No work** is done, either by or against gravity, during displacement in such a case.

The **upper part** of a body always **presses,** in virtue of its Weight, upon the lower.

In some cases it is essential, in surgical practice, to relieve the lower part of the body from the Weight of the upper part: and this is sometimes effected by **suspending** the upper part of the body by means of straps.

Density.—Quantity of Matter, or **Mass, per unit of volume** (grammes per cub. cm.) Example: Density of lead (11·35 grammes per cub. cm.) = 11·35.

Specific Gravity.—**Weight** of a given **bulk** of a substance as compared with the Weight of the **same bulk** of **water.** Take 3 cub. cm. of lead; the Weight of this is 33403·05 dynes; the Weight of 3 cub. cm. of water is 2943 dynes; the ratio between these is $\frac{33403 \cdot 05}{2943}$ = 11·35.

Density and Specific Gravity are thus **numerically identical.**

To find the Densities, or the Specific Gravities, of substances the following methods are in use:—

Solids.—1. Weigh in air (say m grammes): drop into water in a graduated tube and see by how many cub. cm. the water rises in the tube (say v cub. cm.); then we know the **mass** m and the **volume** v, and the Density is the quotient m/v. Graduated tubes for this purpose are called **pycnometers.**

2. Find the **weight of water** which is necessary to fill a little flask (a "**specific gravity flask**") up to a certain mark on the neck. Find the **weight in air** of the body in question. Drop the body into the flask; then bring the level of the water to the same mark, with the aid of a pipette and some filter-paper if necessary: and find the **weight** of the **contents** of the flask. We can thus find the **weight** of the quantity of water which has had to be **removed** in order to maintain the

original level. The **weight of the body** itself, divided by the **weight** of the quantity of **water removed**, gives the sp. gr.

3. Weigh the body in air: then hang it from the pan of the balance, so as to suspend it in water, and again weigh. It now **weighs less**: it has apparently lost weight equal to the weight of its own bulk of water (**Archimedes' Principle**). Therefore divide its **weight in air** by the apparent **loss** of weight in **water**; and this gives the sp. gr.

In **Jolly's spring balance** for measuring sp. gr., a long spiral of wire is made to act as a spring balance, first when the object to be examined is in free air, and then when it is immersed in water. The water can be raised or lowered until the object stands in the water, just immersed and no more.

The apparent loss of weight in water may also be found by a **Nicholson's Areometer.** This is a bulb with a vertical stem, so loaded that it may float vertically in water, with the stem vertically upwards. The stem bears two little pans; and in the upper pan we place the body to be tested, along with masses sufficient to make the instrument sink in the water to a certain level. The lower pan is then under water, and we transfer to this pan the body we are testing. The instrument does not now lie so low in the water; but we add masses in the top pan until the former level is restored. The Weight of these masses, **added** in the upper pan, exactly represents the Weight which the solid body under examination has apparently **lost** through being submerged.

4. If the solid be **lighter than water**, such as cork, apply the method No. 1 above; but sink the cork by letting down after it into the graduated tube a piece of lead of previously ascertained volume. The Volume of the cork can thus be found; and it is supposed that we know its Mass; whence we can find its Density.

5. If the solid be **acted upon by water**, find by any of the above methods its sp. gr. in comparison with any suitable liquid of known sp. gr. If a solid substance be 1·3 times as heavy as chloroform, and chloroform 1·5 times as heavy as water, the solid is $1·3 \times 1·5 = 1·95$ times as heavy as water; that is, its sp. gr. is 1·95.

6. If a solid **float** in water, it will float, supposing its sp. gr. to be 0·8, with 0·8 of its whole bulk beneath the water-level and 0·2 above it. This would not, however, form a practical basis for the estimation of the sp. gr. of a solid; but it is applied in the estimation of that of a liquid.

Liquids.—1. Find the weight of the quantity of water necessary to fill a **specific gravity flask** up to the marked level; empty and thoroughly dry the flask (as for example by rinsing successively first with alcohol and then with ether, and sucking air through the flask by means of a glass tube); refill to the same mark with the liquid to be tested, and find the weight of the quantity necessary. Then the weight of the liquid, divided by that of the equal volume of water, gives the sp. gr.

In **Ostwald's specific gravity flask**, for determining the sp. gr. of liquids, the liquid is sucked in until it stands with one end at *a* and the other at *b*; and the whole is then weighed.

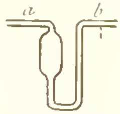


Fig. 81.

Schmaltz's capillary pycnometer, for ascertaining the sp. gr. of blood, is a small straight tube with fine-drawn ends, containing in all about $\frac{1}{10}$ cub. cm. This is filled with water and weighed, then refilled with blood and again weighed. The weight of the tube itself being known, this gives the requisite data.

2. If a solid immersed in water appears to lose 2 grammes of its weight, while if immersed in chloroform it appears to lose 3 grammes, then the sp. gr. of the chloroform is $\frac{3}{2} = 1{\cdot}5$ (**Archimedes' Principle**).

3. On the principle of paragraph 6 above, an object which sinks to a certain depth in water will sink more deeply in a liquid lighter than water, not so deeply in a heavier liquid. **Hydrometers**, alcoholometers, galactometers, urinometers, etc., are objects which float: they consist of a bulb of glass bearing a graduated stem above and loaded with mercury below, so that they may float with the stem vertical. The instrument-maker ascertains at what heights they stand in liquids of known specific gravities, and graduates them accordingly. When such instruments are used, the liquid is placed in a glass vessel, and a piece of black paper may be arranged to serve as a background, in order to facilitate the reading of the level at which the instrument stands. If a liquid be muddy, its density, as ascertained by a hydrometer, urinometer, or the like, is the density of the muddy liquid as a whole, not that of the pure liquid in which the mud-particles float.

4. **Rousseau's Densimeter** is a similar instrument which is floated in water. At its summit there is a little cavity, which can hold 1 cub. cm. of the liquid to be tested. The heavier that liquid, the deeper will the densimeter sink: and the instrument is graduated accordingly.

5. **Fahrenheit's Areometer** is similar, but bears a little pan at its summit. Suppose it weighs 80 grammes, and that when it is floated in water, an additional weight of 20 grammes in the pan, making 100 in all, will sink it to a certain level; and if on its being floated in ammonia solution, 8 grammes are found

sufficient to sink it to the same level, making 88 grammes in all; then the sp. gr. of the ammonia solution is $\frac{88}{100} = 0·88$.

6. **Specific gravity bulbs** are sold, marked with numbers, which sink in liquids of sp. grs. less than that marked on them, and float on heavier liquids. In liquids of the correct sp. gr. they float at any depth. A handful of these bulbs is let down into a liquid; some sink, some float; the one exactly corresponding, if there be one, is at rest anywhere within the liquid.

Gases.—Usually by finding the weight of the quantity of air which occupies a given copper vessel, and then finding that of the quantity of the given gas which occupies it at the same temperature and pressure.

The Density of gases varies from that of hydrogen (0·0000895682 grammes per cubic cm.) to that of heavy vapours of liquids. The density of air is 0·0012932 grms. per cub. cm. That of liquefied acetylene is 0·34; that of iodide of methylene is 3·33; that of a saturated solution of cadmium borotungstate is 3·6; that of mercury is 13·596. That of lithium is 0·5936, and that of hammered platinum is 21·25.

Divisibility.—Since Matter consists of distinct and separate **molecules**, it is possible to obtain matter in a state of very fine division.

The **sodium** compounds floating about in **the air** of a room perceptibly affect the spectroscope flame: a grain of **musk** will perfume a room for years without perceptible loss; the escape of a minute bubble of **sulphuretted hydrogen** into a large room is distinctly perceptible.

The **molecules** of matter stand more or less apart from one another in the **Ether**; and the properties and states of Matter very largely depend upon the relations of Molecules to one another and to this all-pervading Ether.

The Ether

It is difficult for us to realise that hardly more than seven generations have passed away since people first fully grasped the idea that our **atmosphere** exists, and that we live and move at the bottom of an ocean of atmospheric **air**, the **weight** of which presses upon us and upon all objects which are within our reach. When this was first stated it created considerable stir among the scientific circles of the time ; but it has now become a commonplace of human thought. At the present time we are in much the same position with regard to one of the fundamental facts of the Universe, the existence of an **all-pervading Ether**. The existence of this is only an **inference** from the facts observed by us, but so also is the existence of the Atmosphere, or of any familiar external object ; we believe it to exist because its existence would explain the facts of our own consciousness.

The **Ether**, then, is an all-pervading medium, in which the sun, the earth, the moon, the planets, and the stars move ; which is something like or **analogous** to a thin **jelly**, though it would not be safe to say that it is structureless, for it is probably not so ; which can be set in **oscillatory** movement, with the consequence that longer or shorter **waves** are propagated in it, which Waves we come to know of from their giving rise to the phenomena of **Light**, of **Radiant Heat**, of **Actinic radiation**, and of **Electromagnetic Oscillations** ; which can be put under **stress**, with production of what are called **Electrostatic Phenomena** ; which can on being **released** from stress, have a thrill propagated through it, which gives rise to the phenomena of **Electric Discharge** and the **Electric Current** ; and which can be set in whirlpool or **vortical** motion, with the production of phenomena which we associate with the name of **Magnetism**.

This Ether is considered, though not with eertainty, to be about $\frac{936}{1000,000000,000000,000000}$ times as heavy as water ; and it is believed that in order to effeet a given transverse deformation in it, the foree required would be $\frac{1}{1000,000000}$ that required to effect a similar deformation in steel. The consequence of this is that a comparatively **slowly-moving** body may travel in this Ether with ease, for the Ether readily **closes** up behind it and leaves no trace of any rupture. A rapidly **vibrating molecule** of Matter may, on the other hand, move too fast to allow the Ether to flow round it, and the Ether may thus be set in Vibration; and **waves** may be set up in the Ether corresponding to the vibrations of that molecule.

A serious difficulty in the examination of the Ether is presented by the circumstance that **by no means** known to us can we **extract** it even partially from a given space: nothing of the nature of an air-pump can remove it, and even what we call a perfect **Vacuum** is still filled with this Ether. Even if we could produce a perfect vacuum, we would only have taken out the ordinary Matter, none of the Ether. The necessary consequence of this is that we cannot compare the conditions say of a flask containing Ether, and of a flask containing none or containing less than the former. With Air we can do this; and this enables us to study the properties of the air by direct observation: but with the Ether this is not yet possible.

The **best vacuum** is produced by applying the air-pump as far as we can, and extracting the remaining molecules **chemically**: for example, if carbonic acid gas be highly rarefied, we may use caustic potash to absorb almost the last traces of it.

Molecules and Atoms

In his study of Chemistry the student will have learned that we have **no means of destroying Matter**, though we may make it change its combinations and sometimes become invisible, as for instance when a candle is burned and its material becomes converted, by combination with the oxygen of the air, into invisible carbonic acid gas and water-vapour. He will also have learned that Matter in all its forms is composed of, and may be resolved or analysed into some, more or fewer, of about seventy different Kinds of Matter or **Elements**, and that we have **no means** as yet of **transforming** one element into another. He will also have been told what the chemical evidence is on the ground of which chemists believe that all matter is made up of very small particles, called **Atoms,** which we do not know how to split up any further; and that by far the most part of the Matter in Nature is made up of agglomerations or combinations of these atoms into **Molecules,** which are the smallest masses or quantities of any given kind of substance that can normally exist in the **free state.**

For example, a piece of chalk might, in our imagination, be cut down and scraped until we had arrived at the smallest possible mass of chalk; this would be a molecule of chalk; but if we tried to cut this down any further, the most we could do would be to break the molecule up into an atom of calcium, one of carbon, and three of oxygen. Of course the student understands that this does not refer to anything which we could actually do with a knife or the like instrument; the molecules are so small that we could not get at them singly by any such means. And in truth, what we know about Molecules and Atoms is, that it is impossible to understand how the actual phenomena can occur without assuming that they exist; and on that footing we feel justified in saying that they do exist. If we take that plunge, if we say boldly that they do exist, then the whole series of phenomena becomes stateable with comparative ease.

In a molecule the atoms range in number from 1 in mercury to over 30,000 in protoplasm.

The Chemist says he knows that Atoms and Molecules exist, because he could not otherwise explain how matter enters into combination in accordance with the **Law of Fixity of Proportion** and the **Law of Multiple Proportions**; and further, he arrives at **Avvogadro's Law**—that in all Gases there are, within equal volumes, always the same number of molecules, provided that the temperature and the pressure are the same. For example, a cubic centimetre of hydrogen contains the same number of molecules as a cubic centimetre of alcohol-vapour at the same temperature and pressure, though each molecule of alcohol-vapour contains more atoms (two of carbon, six of hydrogen, and one of oxygen) than a molecule of hydrogen does (two atoms of hydrogen).

Apparent exceptions to Avvogadro's Law he explains in two ways: (1) there may be an **abnormal number** of **atoms** in the **molecule** of an element, as in the case of **ozone**, in which the molecule contains three atoms instead of two as in ordinary oxygen, with the consequence that a given bulk or volume of ozone (that is, a given number of moleeules) weighs $1\frac{1}{2}$ times as much as the same bulk or volume (that is, the same number of molecules) of ordinary oxygen: and (2) there may be a break-up or **dissociation** of the molecules, as in the case of the vapour of chloride of ammonium, NH_4Cl, which vapour occupies twice as much volume as it ought to do according to the theory. This vapour is therefore supposed to contain not molecules of (NH_4Cl) at all, but a mixture of molecules of (NH_3) and (HCl) separately. This last supposition would double the number of molecules in a given mass of the vaporised (NH_4Cl), and would therefore double the volume which a given quantity of chloride of ammonium vapour should occupy; and it would thus make the theory fit the facts. That this is a sound hypothesis is shown by the circumstance that if we try to pass the vapour of chloride of ammonium through a long tobacco-pipe stem, ammonia oozes through the porous clay more rapidly than hydrochloric acid does; which shows that the ammonia and the hydrochloric acid are not united, but are separate in the vapour of ammonium chloride, for each gets through the porous clay in its own way, independently of the other.

The Chemist does not usually concern himself much with the **structure** of an **atom**: what he is concerned with is its relation to other atoms in its combinations with them to form a complex Molecule. But he is clear that atoms of different elements differ in their **mass**, that is to say, in the Quantity of Matter in each, and therefore in their **weight**; and he is also clear as to this, that whatever the physicist may tell him is the mass or weight of a single atom, **all** the **atoms** of any given **element**, whatever be their mass, have exactly **the same mass**, so that they all have the same weight, and are like manufactured articles, all similar and mutually **replaceable**. How this comes to be is a question which transcends both Chemistry and Physics; but the fact simplifies the phenomena of Nature to an extraordinary extent.

So far, then, the Chemist; but the Physicist has his own conclusions also. Except in such matters as Electrolysis he has not hitherto concerned himself much with the chemist's distinction between Atoms and Molecules; but during recent years the distinction has become one of importance in Physics also, for **dissociation** has had to be called in in order to explain many abnormal phenomena. The physicist has definitely concluded that matter **is not homogeneous**, but must have some kind of grained structure.

Many years ago Lord Kelvin, then Prof. Wm. Thomson, set before himself the question: If there be this grained structure, **what is the size of the grains?** If a wall be built of bricks, and therefore cannot be made less than one brick thick, we get an idea as to the size of the bricks if we can find what is the thickness of the thinnest possible brick wall. Similarly we get an idea as to the size of the molecules if we can find the thickness of the thinnest possible sheet of Matter. Prof. Thomson traced this subject out along different lines.

Firstly, we may melt together zinc and copper to form brass; it is clear that not more than a certain amount of Energy is liberated in the form of Heat, through the satisfaction of the mutual attractions, in this operation; but zinc and copper are known to attract one another when brought in contact, a phenomenon which is dealt with under Electricity. A great number of sheets of copper and zinc would evolve a great deal of Energy through the satisfaction of this mutual attraction: and as such an amount of Energy is not forthcoming upon melting copper and zinc together to make brass, we infer that the number of such possible sheets is limited, and find by calculation that it cannot exceed some 1000,000000 to the centimetre. A molecule of copper or zinc will therefore have a maximum diameter of $\frac{1}{1000,000000}$ cm.

Secondly, a soap film has a certain minimum possible thickness, beyond which any further stretching would volatilise it. This is again about $\frac{1}{1000,000000}$ cm. There are other considerations which point in the same direction.

In 1883 Sir William Thomson revised his previous estimates, and concluded that if a globe of water the size of a football were magnified to the size of the Earth, the molecules of the water would each occupy a space magnified to a size something between that of a small shot and that of a football.

Next, as to the **nature** of these **molecules**. It will not do to look upon them as hard balls or anything of that kind, because they are too capable of entering into vehement **vibration**, and because they have considerable **action upon one another**. The most promising suggestion which has been made is Lord Kelvin's, that they are made up out of the **Ether itself**: that they are essentially **analogous** to the **smoke-rings** which are blown from cannon or from the lips of a skilled smoker, or from exploding bubbles of phosphuretted hydrogen, though they may have more entwined and complicated forms than these simple rings. Such smoke-rings have properties which very closely remind us of those which Molecules appear to have. They are due, in the air, to Friction; but in a frictionless fluid such "**vortex-rings**" could not be formed at all; and it appears that Molecules of this kind, in the Ether, could not originate except by an act of special creation of some kind. But once granted that such "vortex-rings" exist in the Ether, they could **move about freely** in it; they would each have an **invariable volume**: if two of them struck one another they would **rebound** and **oscillate**, undergoing **vibrations**: they could **not** be **cut**, for they would be repelled from the edge of any conceivable knife; and they would be capable of considerable **changes of form**.

This theory explains many other facts with great readiness: but we are still in ignorance as to the cause of Gravitation and as to the real inner meaning of the term physical Mass, as well as of the relation of the chemical Atom to the chemical Molecule in a compound.

Let us take it, then, that Matter, as we know it, is made up of **molecules** of some kind. We have still to learn something about the behaviour of these. In the first place, there is no case, apparently, in which the molecules are so close together that they cannot move; they **always do move**. Their movement is of three kinds, **trans-**

lational, rotational, and vibrational : and these movements together correspond to a certain amount of Energy, mostly Kinetic, which energy is itself known by the name of Heat. Then again, the vibrations of the molecule set the surrounding Ether in motion; and the Energy imparted to the Ether from the vibrating molecules, and transmitted through the Ether to a distance by means of Ether-waves, is called Radiant Heat, or the Energy of Light, or Actinic Radiant Energy, or the Energy of Electro-magnetic Waves, as the case may be, according to the length of the waves produced.

If the particles are thus to a certain extent free to undergo a movement of Translation, they must each be able to travel for a certain distance before colliding with any other molecule ; and the average length of this distance is called the mean free path.

Ultragaseous Matter

Suppose that a very few such Molecules are introduced into a perfect Vacuum. How will they comport themselves? They will, in virtue of their kinetic energy of translation, hurl themselves against the wall of the vessel containing them ; by this they will tend to break the vessel, by impact from within : they will thus exert a certain pressure upon the vessel, which will depend upon the number of them and upon their average velocity. After meeting the walls of the vessel they will rebound ; but their numbers are so small, and their diameters also so small, that each molecule has only a very slender chance of encountering any other molecule, and at any rate the most part of the molecules will again encounter the walls of the vessel containing them, and will again rebound. When they rebound they spin and vibrate ; and their vibration sets the surrounding Ether in motion.

Mr. Crookes has succeeded in realising a condition something like this; he managed to extract about 99,999999 molecules out of every 100,000000 in a given bulk of air in a glass tube; and then the mean free path of the molecules was something like 4 inches. Up to that limit of distance, the particles, once repelled, in his apparatus, from an electrically charged surface, seemed to travel uninterruptedly in Straight Lines; and for this reason he gave this form of matter, which is in reality no more than an exceedingly rarefied form of Gas, the name of **Radiant Matter.** He has devised a number of very attractive experiments, the conduct and result of which all depend upon the long free path and on each molecule being independent of every other: there are so few molecules present, that any given molecule remains unhampered by any impacts with its colleagues, or by any attraction towards or repulsion from them.

As we go on increasing the number of Molecules within our given space, the **mutual impacts** or collisions of the molecules themselves become **more frequent.** On the average, any given molecule will not be able to travel so far without colliding with some other molecule; and the **mean free path** is thus **shortened.** When the molecules have become as numerous as they are in ordinary hydrogen gas, under ordinary conditions (somewhere about 1000,000000,000000,000000 in a cubic centimetre) their mean free path is reduced to about $\frac{1}{100000}$ cm., and the number of impacts between any given molecule and its fellows becomes about 17,750 millions per second. We have then arrived at the condition of **ordinary Gas,** in which the Molecules have only a **very small mean free path.**

Gases

We may distinguish in ordinary Gases two conditions which merge into one another; and we may take as illustrating these conditions the two extremes, a **highly-rarefied gas** (one in which there are *comparatively* few molecules to the cubic centimetre), and a **highly compressed gas** (one in which there are relatively many).

The difference between these is, that in the former the molecules do not appreciably affect one another by their **mutual action**; in the latter they do, because they are more crowded together.

In speaking of Gases we may, in the first place, deal with them as if they all acted as highly-rarefied gases practically do; in other words, we may deal with them as "**ideal perfect gases**"; that is, we may **neglect** in the meantime all those properties which depend upon the **mutual actions** of their Molecules. We are thus enabled to state the properties of Gases in the least complicated manner: and then we shall see that the mutual actions of the molecules of a gas cause **anomalies** in its behaviour, which render the properties of a gas less simple than those of an ideal perfect gas would be.

A Gas has **no free surface**, and **occupies any space** within which it may be confined: that is to say, its Molecules find their way into every part of the cavity and strike against every part of the bounding walls. If the cavity be enlarged, the gas **expands** so as to fill it.

It exerts upon every part of the bounding walls the **same pressure** per sq. cm.; or rather, it practically does so within vessels of moderate size.

If we set ourselves the problem, what the **average speed** of the Molecules in their free path must be before they can produce the observed Pressure, we find that it can be solved: but it turns out that this average speed is enormous. In hydrogen it is 184,260 cm. per second, or over 4000 miles an hour: in oxygen it is over 1000 miles an hour.

Note, however, that this is an **average** speed. If the speed of any given molecule in our atmosphere happened to exceed about 25,000 miles an hour, a departure from the average which in the case of **hydrogen** seems quite conceivable, and if it happened to have a clear path before it, the molecule in question might dash away from our atmosphere and escape: for the earth's retarding attraction would not be sufficient ever to bring its velocity down to nothing. It has been suggested that by this means we may have lost all the hydrogen in our atmosphere, molecule by molecule. In the case of the moon the corresponding necessary velocity would be only about 2600 miles per hour—a circumstance which would render all its atmosphere able to escape very readily and to leave the moon atmosphereless, as it appears now to be.

If we take a volume of Gas in a cylinder, with a piston of a given weight or loaded by the weight of a given mass, the piston will not sink beyond a certain depth. The Weight of the piston tends to pull, and the Weight of the external atmosphere tends to push, the piston **downwards**; but the Molecules of the gas within the cylinder **bombard** the piston; they thus **press** upon it and tend to move it **upwards**. Between these opposed forces the piston remains at **rest**.

Fig. 82.

Let us now put a heavier mass upon the piston; the downward pull due to gravity is now greater, and the piston sinks; but its downward motion is arrested when the molecules per cubic centimetre become so numerous in the gas within the cylinder that their increased bombarding effect on the piston, that is, the **increased pressure** of the Gas, is equal to the increased compressing Force. But the gas in the cylinder must be **compressed** before this condition of things is reached. Gas is therefore **compressible**; and the law of its compression is that its **volume varies** (if its temperature remain the same) **inversely as the pressure** to which the gas is exposed. Conversely, the **pressure** which a given quantity of gas exerts is **inversely proportional** to the **volume** which it is made to occupy. These are different forms of what is called "**Boyle's Law.**"

Next, we must define the **Absolute Temperature** of any substance as its Temperature * (in Centigrade degrees,

* We have no hesitation in assuming that the student is acquainted with the ordinary meaning of the word Temperature as shown by an ordinary thermometer. On the Centigrade Scale water freezes at 0° C. (=32° Fahrenheit), and boils at 100° C. (=212° F.)

or degrees on an ordinary Centigrade thermometer) reckoned on the footing that $-273°$ C. is an **Absolute Zero.** Thus a temperature of 15° C. is 288° Abs. Then, the **volume** of a gas, if the pressure remain the same, is directly **proportional** to its **Absolute Temperature** ; and if its Volume be compelled (by increasing the external pressure or by confining the gas within a rigid vessel) to remain the same, the **pressure** varies directly as the Absolute Temperature. If the Pressure and the Volume both vary, then their *product* is proportional to the Absolute Temperature (**Charles' Law**).

There is a reason for all this. The Absolute Temperature is itself a measure of, it is proportional to, the **average kinetic energy** of the molecules ; and so is the product of the Pressure into the Volume. That product and the Absolute Temperature are therefore proportional to one another.

In order to prevent the pressure within a heated gas or vapour from becoming excessive, a **safety valve** is often used. Here there is a plug which is squeezed into an orifice in the boiler by a spring or weight : the internal pressure is not able to eject the plug until it attains a certain amount. When this occurs the valve is forced open. Gas or vapour then escapes, and relieves the internal pressure.

In **expansion drop-bottles** a little groove is cut in the stopper and bottle-neck ; the bottle is inverted and held in the hand ; the hand warms the contained air, which thereupon expands and drives out the liquid in drops. The same result may sometimes be seen in **fountain pens**, especially when nearly empty.

Since the Volume of a perfect gas (when the pressure is kept constant) is proportional to the Absolute Temperature, and since a rise of temperature from 0° C. to 1° C. would be a rise from 273° Abs. to 274° Abs., a rise of temperature from 0° C. to 1° C. would correspond to an increase of volume in the ratio of 273 to 274, or 1 to $1\frac{1}{273}$. The proportionate increase in volume is thus, for 1° C., equal to $\frac{1}{273}$, and this fraction is the **Coefficient of Expansion by Heat.** If all gases were perfect this would be the same in all gases ; and if air were a perfect gas, we could use a quantity of air enclosed in a flask as an **air thermometer**, for it would not be difficult to find means for ascertaining how much it expanded during a given change of temperature.

Suppose that on being heated from 10° C. to an unknown temperature, the volume of the enclosed air rose in the ratio 1 : 1·04 ; the Absolute Temperature is 1·04 times what it was at 10° C., that is, it is $1{\cdot}04 \times 283$; this is 294·32° Abs. or 21·32° C.

The absolute volume of expansion per degree would, in a perfect gas, be the same for each successive degree of temperature : and equal increments in the volume of such a gas would indicate equal increments of temperature.

If we mix two quantities of the **same gas** at the **same temperature**, the Temperature of the whole remains **equal** throughout ; that is to say, the average Kinetic Energy of the molecules remains the same throughout, and the molecules have the same average velocity in all parts of the gas.

If we mix two quantities of the **same gas** at **different temperatures**, the Temperature of the whole becomes **equalised** throughout ; the average Kinetic Energy of the molecules becomes the same throughout, and the molecules come to have the same average velocity in all parts of the gas.

If we mix two quantities of **different gases** at the **same temperature**, again the Temperature of the whole remains equal throughout : and if we mix different kinds of gases, say oxygen and hydrogen, at **different temperatures**, the mixture again comes to a common temperature. In either case the average kinetic energy of the molecules again remains or becomes the same throughout. But the average translatory **velocities** of the oxygen and of the hydrogen molecules respectively are **not the same.** In order to have equal average amounts of Kinetic Energy, the lighter molecules must have higher average velocities, and the heavier molecules smaller velocities. The **velocities** of the molecules of each kind must be **inversely proportional** to the *square roots* of their respective relative **molecular weights.** The mean velocity of oxygen molecules is thus one-fourth as great as that of hydrogen molecules, because their mass is sixteen times as great.

If we consider two gases, again say oxygen and hydrogen, at the same temperature, but apart from one another, the same principle applies. The mean Kinetic Energy of the several molecules in the two respective gases is the same; and the mean translational velocities are inversely proportional to the square roots of the respective molecular weights.

From this it follows that **equal volumes** of all Gases contain the **same number of molecules** ("Avvogadro's Law"); and from this again it follows that gases which are made up of heavier molecules are themselves heavier in exactly the same proportion; that is, that the **density** of a Gas is directly **proportional** to the **molecular weight** of its component molecules.

Gases thus differ in **specific gravity**; and a heavier gas, such as carbonic acid gas, can be **poured** out of one vessel into another just as water can. Carbonic acid tends to accumulate in wells, etc., and to lie in brewery vats, just as a heavy liquid would do; and if the source of supply be constantly active, the process of Diffusion (p. 80) may not be sufficient to carry the accumulation of gas away.

If we have a **mixture** of gases, the Pressure which it exerts on the vessel containing it is (still on the assumption that the mixture is so far rarefied that there is no appreciable mutual action between molecules of different kinds) the *sum* of the pressures due to the molecules of each kind; and the **pressure** exerted by **each component** of the mixture is **independent** of the pressures exerted by the rest of the components ("**Dalton's Law**").

If we have the molecules in one region of a gas moving with greater average velocities than those in another, this inequality will be brought to an end: more rapidly-moving molecules will by collision part with their energy to others, and these again in the same way to others beyond them; and thus we have Transference of Energy from one part of a gas to another. This process is what is known as **Conduction of Heat** in a Gas; for the **Heat** of a **gas** is itself the **kinetic energy** of the **molecules**.

It is convenient to use this phraseology though it is slightly in error. The Energy of **translation** of molecules is kinetic; the energy of **rotation** of molecules is again kinetic; but the energy of oscillation or **vibration** of molecules is half kinetic, half potential. This last renders the above phraseology to that extent erroneous; but the error has no consequences so far as we are concerned here.

Further, if we have two layers of gas, one of one kind, another of another, and leave them to themselves, we find them become **mixed**. The **molecules** of one kind **wander** among those of the other: and the result will, if sufficient time be allowed, be complete mixture by this process of **Diffusion of Gases**. But the **time** taken to effect complete admixture in the air of a room, or in the coal-gas in the interior of a gas-holder where rich and poor gases are let in, is far greater than the time required to ensure complete admixture in experiments on the laboratory scale.

Diffusion is illustrated by the exchange between the tidal air and the residual air in the **lungs**; by **ventilation** through opening the window on a calm day, a process whereby the air is gradually exchanged, but the **dust** in the room is not affected, for the process is a molecular one merely; by the diffusion of **odours** in an apartment: by the diffusion of oil-of-peppermint vapour through a leak in **drain pipes** into which the oil has been poured; or by the diffusion of **disinfecting gases**.

Again, if we drive a current of a gas through a bulk of gas, we find the stream slacken off: some of its molecules wander off into the comparatively-still surrounding gas, and some of the comparatively-slowly moving particles of that gas wander into it; and thus the momentum of the stream continually diminishes. This phenomenon is known as the **viscosity** of gases, the apparent Resistance to the onward Flow of streams of gas.

To this viscosity or Internal Friction of the air is to be attributed the resistance which objects encounter to motion through the air. The film of air nearest the surface of a moving body practically remains unchanged, and the moving body has to drag this film of air past the surrounding air. Falling water is thus broken up into mist. Conversely, when a body falls through air it drags some air down with it.

This circumstance is turned to account in **Sprengel's** and **Bunsen's air-pumps**, in which mercury or water respectively, falling in a stream down a tube A, drag air or other gas with them from a side-tube B, and may thus exhaust air or other gas from any vessel with which that side-tube B may be connected.

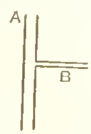


Fig. 83.

The Bunsen pump is used in the **filtration** of liquids, and the Sprengel for such purposes as the **exhaustion** of the bulbs of incandescent electric lamps or of Geissler tubes. If in a Sprengel the lower end of the tube A be bent upwards and immersed under mercury, the gas withdrawn through B may be **collected** in a test-tube.

When a body moves in air, the air in front of it is pushed forward, the air at the side is dragged along with the moving object, and the **partial vacuum** left behind is readjusted by an inrush of air particles from all sides. The last may, as in the case of **rifle bullets**, be so abrupt as to cause a noise, through mutual impact of the molecules; and this noise is the "singing" of the bullet as it flies. All this causes resistance to the onward movement. A **rain drop**, as it falls, cannot acquire more than a definite limited velocity: no more can a **balloon parachute**, when once it has opened out under the expanding action of the air through which it falls; and a rotating vane (**Foucault's vane**) is very generally used to regulate the speed of rotation of clockwork, of physiological drum recording apparatus, etc., for its speed cannot exceed a certain maximum, which varies with the force exerted by the driving spring.

If we make the Temperature and Pressure of a gas undergo alterations, then, assuming always that there is no chemical change induced thereby, if we restore the original temperature and pressure we restore, simultaneously and completely, the original volume. The **previous history** of a **gas** thus makes **no mark** on its condition at any moment. If we induce a gas to become **compressed** by increasing the external Pressure, we must **keep up** that external **pressure** if we mean to keep up the compression ; and if we let go, and allow the pressure to fall back to its original value, the gas expands to its original volume. All this is expressed by saying that the **elasticity of volume** of a gas is **perfect** ; its tendency to restitution is **continuous**, and its **restitution** is **perfect** when the surrounding conditions are again the same as at first.

Suppose that we have a given mass of gas confined within a given volume, as in Fig. 82, and that we **suddenly** force the piston in. We have done a certain amount of **work** in forcing the piston in, against a continuously increasing pressure, through a certain distance. What becomes of the Energy corresponding to this work? It has been imparted to the gas, and makes its molecules move more rapidly; that is to say, **Heat** has been imparted to the gas. This Heat, being a form of Energy, can be measured in ergs or in foot-pounds, and the Heat imparted to the gas would, in ergs or in foot-pounds, be exactly equal, in a perfect gas, to the Work done upon it. The gas therefore **becomes heated** when it is suddenly **compressed** by the application of an exterior pressure. Conversely, if we allow a gas to **expand**, doing work against an exterior pressure, it loses molecular kinetic energy ; that is to say, it loses Heat, and becomes **cold**.

In both these cases it is assumed that the operation is so conducted that Heat **cannot escape** from the compressed gas or travel towards the expanding gas ; and compression or expansion of this kind, in which there is no travelling of Heat either from or towards the gas dealt with, is called **Adiabatic** compression or expansion.

If, on the other hand, the gas be suddenly compressed or expanded in a metal vessel surrounded by a mixture of ice and water at 0° C., it will be maintained at the same temperature: in the case of compression, by the escape of heat from it to the mixed ice and water: in that of expansion, by the travelling of heat from the ice and water to it. In the former case some of the ice melts: in the latter some of the water freezes. In such a case as this the gas itself gains or loses nothing in the way of molecular kinetic energy, and all the Energy corresponding to the Work done is as it were passed through the gas, without accumulating or diminishing within it.

If there be mere expansion of a perfect gas, as where such a gas is allowed to flow from a full vessel A to a vacuum-chamber B, the whole being surrounded by rigid walls, so that the external pressure plays no part in the phenomenon, the perfect gas would retain on the whole the same average temperature, but the portion left in the vessel A will be colder, while that in the vessel B will be warmer than the average.

It will take a certain quantity of Heat, a certain number of ergs or foot-pounds of Heat, to raise a given quantity of a gas through 1° C. of temperature. To raise its temperature through 2° C. will take twice as much; and so forth. In this there are two cases to be noted.

1. If our perfect gas be not allowed to expand while being heated, then the whole of the Heat supplied goes towards raising the Temperature; and the amount of Heat (the number of ergs of Heat) which must be supplied, in order to raise the Temperature of a unit of mass, namely, one gramme, of the gas in question by one degree C. is called the Thermal Capacity of that gas: in this case the Thermal Capacity at Constant Volume.

2. If the gas be allowed to expand freely while being heated, the external Pressure being maintained constant, work is being done, and Energy expended at the same time, in overcoming the external pressure. Therefore, in this case, more Heat must be supplied before we can succeed in raising the temperature of our one gramme through 1° C.; and thus a Gas has at Constant Pressure a different Thermal Capacity from that which it has at Constant Volume. In a perfect gas the Thermal Capacity at Constant Pressure would bear to the Thermal Capacity at Constant Volume the ratio of 5 to 3, or $1{\cdot}66\dot{6}$ to $1{\cdot}000$.

The thermal capacity in a perfect gas would depend only on the amount of energy which would be required in order to increase the energy of translation, spin, and vibration of each molecule by a certain amount; and it would therefore be independent of the pressure or of the already-existing temperature.

If a **local compression** be set up in a Gas, its Molecules will there be more closely crowded together. This compression will be **propagated** through the gas with a Velocity which has been computed for a perfect gas, by Clerk Maxwell, at $\frac{745}{1000}$ times the average translational velocity of the molecules themselves. Similarly for a rarefaction; and if the local disturbance be an **alternation** of compressions and rarefactions, the result will be the propagation of a **wave-motion** through the gas. In this wave-motion, at any point, the direction of displacement of the particles is backwards and forwards in the same direction as that in which the wave is itself travelling; that is, the vibration is not of the transverse but of the **longitudinal** type.

The **velocity** of propagation varies according to the law that the *square* of that Velocity is directly proportional to the **Absolute Temperature**, and inversely proportional to the **density**, of the gas. In oxygen, for example, which is 16 times as heavy as hydrogen, the velocity of the propagation of waves of compression and rarefaction would be $\frac{1}{4}$ as great as in hydrogen at the same temperature,—a ratio which would be exact if those gases were perfect gases, or were so far rarefied as to act as perfect gases.

When we confine ourselves to one and the **same gas**, it **does not matter** what the degree of **rarefaction** or compression of that gas may be; the velocity of propagation of a wave-motion is not affected by this, at any rate in perfect gases, for the velocity of propagation depends upon the speed of travel of **single molecules**: if the gas be rarefied, though there are fewer molecules to do the work, each has a longer free path: and this provides complete **compensation**.

It must be remembered that the actual Temperature of the gas at a place where it is subjected to sudden compression is increased: and therefore the actual Velocity of propagation of compressional Waves is the same as the velocity through a gas heated by a compression during which no heat is allowed to escape. This was for a long time a puzzle, since the speed of propagation of wave-motions in gases, as found experimentally, did not agree with the early theory of Sir Isaac Newton, in which this consideration had been lost sight of, with the consequence that the calculated velocities of propagation of waves were materially smaller than those actually observed.

We know that the **molecule** has **three kinds of Energy**, that of Travel or Translation, that of Spin, and that of Vibration. These three remain steadily **proportionate to one another**, so that if one falls off, the others fall off too. In the **steam-engine** the piston is driven along the cylinder by the bombardment of the molecules as they travel and hit the piston : and as their Energy of Translation is being transferred to the piston, the other forms of Energy are being drawn upon, and contribute to the work done upon the piston.

In some departments of Physics the **vibrations** of the **molecules** assume leading importance. In a gas each vibrating molecule, as it executes its free path between one collision and the next, vibrates freely, like a sounding tuning-fork thrown through the air; and as it can, in virtue of its own vibration, impose vibration upon the surrounding Ether, we may be able to detect the existence and learn something about the nature of the vibration of the molecule itself. This we do through the phenomena of **Radiant Heat** and observations made with the **prism** (p. 259), which show that the Ether-waves which radiate from **highly rarefied** heated Gases correspond to comparatively **simple and regular vibrations** of the respective Molecules themselves. But the **frequency** of these vibrations of molecules is exceedingly great: those which give rise to the undulations in the Ether which are perceptible to us as **Light** are on the average about **550 millions of millions** per second;—the reason being that the Molecules are so elastic and so extremely small.

From the nature of a **perfect gas** it would follow that in such a gas there could be **none** of the results of molecular interaction or **molecular forces** ; no stickiness or toughness, no hardness, no capacity for being in any way stretched, or bent, or twisted, or anything of the kind. If any such operations were effected on the containing vessel, the gas would simply still continue to fill it, and each molecule would wander freely, colliding as it went, from one part of the containing cavity to another.

Ordinary **gases, in bulk**, behave in many respects as if they were Perfect Gases; and we shall therefore now go on to consider their behaviour when at Rest and when in Motion.

General Statics of Gases

A gas is **similar in all directions**; if a little plane be put anywhere within a gas, it will be equally bombarded in whatever direction it is made to turn: the **Pressure** within a gas is therefore the **same in all directions**. And apart from the Weight of the gas itself, the Pressure throughout a gas is the **same at all points**, that is if we compare equal areas; it is the same at the surface as in the substance of the gas; and Pressure of this kind is called **Hydrostatic Pressure**. At the surface it is directed always at **right angles** to the surface, no matter what the form of the surface may be. If we **increase** the Pressure over the surface, the increase of pressure is felt **throughout** the gas: and the pressure per sq. cm. on the surface is reproduced as an equal pressure per sq. cm. at any point in the interior of the gas, **in any direction.** This principle is known by the name of the **Transmissibility** of Gaseous or of **Fluid Pressure.**

But it must be noted that what is here said of Pressure applies only to pressure **per unit of area**: so that if we compare larger and smaller areas we shall obtain larger and smaller Total Pressures within the same gas.

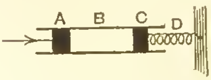


Fig. 84.

If for example we drive the piston A into the tube B filled with a gas, the plug C will be driven against the spring D with a Force equal to the Pressure upon A, if the Area of C be equal to that of A. If C be larger than A, the pressure per unit-area of C remains equal to that per unit-area of A; but as C is larger, the total pressure on C and on the spring is greater in direct proportion to the larger area of C; and the spring C must either be stronger, or will be more distorted when A is pushed in with the same force as at first. If a man were to spend his whole strength in driving A, a pressure will be exerted upon C much greater than his unaided efforts would enable him to apply. If this apparatus be put into the form of Fig. 86, we see that a smaller weight at A will balance a larger one at C; and a small excess weight at A will cause considerably more distortion of the spring at C than it could have caused directly if acting alone. In such a contrivance we have, while A is being pushed in, three things to observe: Work done upon the gas at A, Work absorbed by the gas during compression on becoming compressed and heated, and Work done by the gas upon the spring at C: and the two latter are equal to the first. We observe, therefore, that the gas does not act as a simple Transmitter of Energy, for it itself absorbs some and becomes heated; then as it cools down, if A be fixed in its position, the pressure on the spring D relaxes.

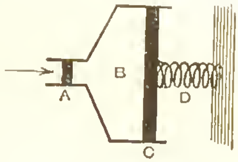


Fig. 85.

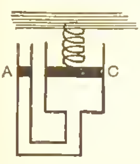


Fig. 86.

So long, however, as the operation is not too rapid, or the fluctuations of pressure at A are not too extensive, so that the gas between A and C does not become appreciably heated, the relation between the Forces is that the product of the force at A into the movement at A is equal to that of the Force at C into the Movement at C; that is, that the work done on the gas at A is equal to that done by the gas at C.

A thin indiarubber bag or tampon, inserted into any of the cavities of the human body and dilated by forcing air into it, will expand until the Pressure per unit of Area of its surface is equal at all points, and equal at each point to the Resistance locally offered by the walls of the cavity and by the bag itself to any further distension. Even without the intervention of an indiarubber bag such cavities may be inflated by air; and the extent to which they will be distended, both generally and locally, follows the same law as when such a bag is used.

The pressure in a gas, p dynes per sq. cm., may be measured in various ways, of which the simplest is by means of a Manometer, Fig. 87. In this there is a glass tube, bent as shown in the figure, and closed at C.

In CD there is a **vacuum**. Between B and D there is mercury. If there be **no** gaseous **pressure** acting upon the mercury B through the open end A, then the mercury will stand at the **same level** at B and at D, if the tube have the same diameter at B and at D. If, however, there be a gaseous pressure at A the mercury rises past D; the mercury at B sinks: there is then a certain measurable **difference** between the levels of B and of D, and the gaseous Pressure supports a **column** of mercury whose **height** is B′D′ cms. (Fig. 88). This column of mercury has a Weight equal, in dynes, to B′D′ × 13·6 × 981 × cross-sectional area of the tube: the Total gaseous Pressure through A is p dynes per sq. cm. × the cross-sectional Area of the tube; whence $p = \{13{\cdot}6 \times 981 \times B'D'\}$ dynes per. sq. cm. The only term in this which needs measurement is the Height B′D′; and it is quite sufficient to know this; so that it is quite common to specify the Pressure by this Height alone, and to speak of a "pressure of so many cm., or so many inches, of mercury."

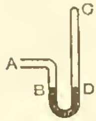


Fig. 87.

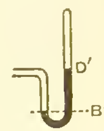


Fig. 88.

Other contrivances may be adopted, in which there is no direct communication between the gas, whose pressure is to be measured, and the interior of the measuring apparatus. Of this kind is the **Aneroid Barometer**, which may be put into the gas in question. In this instrument there is a hollow corrugated case of elastic metal, the interior of which has its air removed: the varying external pressures cause varying **deformations** of the metal case, and the varying deformations are rendered measurable by being made to actuate wheel-gearing and a dial-pointer: or they may be made to actuate a lever provided with a writing-point, whereby the variations of pressure may be recorded, on a revolving drum, on smoked or on white paper. In some forms of Aneroid Barometer there is a coiled closed **tube**, which tube is itself **elliptical** in section and is exhausted of air. As the pressure of the gas surrounding this coiled tube **decreases**, the tube tends to **straighten out** and to become **more circular** in section; and this tendency is made to actuate a dial-pointer. Conversely, as the pressure increases, the tube becomes more pinched out or flattened, and more coiled up. The material of the walls of the tube does not stretch or shrink, and the change of form to a more circular cross-section cannot be effected without a simultaneous straightening out; and *vice versâ.*

Archimedes' Principle.—Of a mass of gas uniform in density, **no part tends** bodily **to rise or sink**; and thus it appears, so far as regards any tendency to fall in obedience to the Law of Gravitation is concerned, to be relieved of that tendency. If a part of the gas were replaced by an equal bulk of anything else which has precisely the same density, that substitute will again neither rise nor sink, but will float in the gas.

For example, suppose the air happened to be at such a temperature that 5000 cub. ft. of it weighed 400 lbs., and that a **balloon** were so constructed that, filled with hydrogen, it would occupy 5000 cub. ft. and weigh exactly 400 lbs.; such a balloon would float in the atmosphere and would neither rise nor sink, for it would simply replace an equal bulk of the air. It would then appear entirely relieved of its Weight.

But the same thing happens even with bodies heavier than air if they be suspended in air; they are, apparently, partially relieved of their Weight, and that to the extent of the weight of an **equal bulk** of the air in which they are suspended.

Take, for instance, a brass "weight" of 1 kilogramme, used in a pair of scales. It will occupy about 125 cub. cm., if we take the density of brass as being eight times that of water: and it will act like the balloon, to the extent that it is apparently relieved of gravity to the extent of the weight of an equal bulk of air, that is, to the extent of 0·16165 gramme. If we are weighing out a lighter substance, say water, the displacement of air by this will be greater: in the case of a kilogramme of water, it will correspond to an apparent loss of weight of 1·2932 gramme. Weighing out a true **kilogramme** of water, therefore, involves some arithmetical working, in order to ascertain what weights should be put in the scale-pan.

Now suppose our **balloon** to **expand** so as to become **lighter** than an equal bulk of air. The **heavier air** around it will **flow under it**, and will displace it, just as mercury poured into water will flow to the bottom and lift the water. The balloon will thus **rise**. It has, of course, no ascensional power of its own: the motive power is the greater pull of gravity upon the denser surrounding air. But the result is much the same as if it had an ascensional force of its own.

If our balloon weighing 400 lbs. came to occupy 5500 cub. ft., it would be 40 lbs. lighter than an equal bulk of air; and it would comport itself as an object of 400 lbs. Mass, pushed up by a Force equal to the Weight of 40 lbs.; that is to say, it would move upwards with an Acceleration $\frac{40}{400}$ or $\frac{1}{10}$ that with which an object would fall freely *in vacuo*.

We need not, however, enclose our bulk of lighter gas or air in a balloon. Suppose a mass of air in a **chimney**, heated by the fire: it rises for precisely the same reason as the light balloon does; the heavier air flows under it and pushes it up. If the air at any one point be continuously heated this operation is continuous, and we have a continuous **upward current of hot air**; but we have at the same time a continuous **downpour of colder air** elsewhere, and it is this which causes the hot air to be pushed up the chimney, to take the place of the colder and heavier air which has descended.

General Kinetics of Gases

When a mass of gas is, by any means, exposed to a pressure which is not the same at all points, the gas **flows** from the point of greater pressure towards all points of less pressure. A gas is therefore a **Fluid**, as distinguished from a Solid. The tendency is for the pressure to become equalised throughout the mass of gas: but during this readjustment there will be a Flow of Gas.

For example, if the head be laid upon one end of an **air-pillow**, the pressure under the head is greater than it is elsewhere; the air within the pillow, therefore, **flows** from under the head and distends the remainder of the pillow, with the consequence that the pressure elsewhere becomes equal to that under the head. When this condition has been attained the flow ceases, and thereafter there is **equilibrium.** The actual Volume of the gas is less, and the Pressure within the gas is greater than they had been before the local pressure was applied; but the degree of compression is equal throughout the air-pillow. It may be noted that an air-pillow is more easily compressed when it is not than when it is fully distended. In the former case the air is under a certain moderate pressure; the additional pressure imposed, which is definite, increases the pressure by a certain percentage: in the latter case this percentage is smaller because the original pressure was greater; and therefore in this case the gas is less compressed.

During the process of readjustment the gas flowing from a compressed region may be caused to pass through a **tube.** This may be seen where a **gasholder** is loaded and drives coal-gas through the gas-mains of a town. The readjustment would come to an end when the loaded top of the gasholder sank to its lowest level, and the flow would then cease; but the flow is kept up by frequently or continuously forcing fresh supplies of gas into the holder, and thus keeping the loaded top of the holder continuously in action. There is thus maintained **a continuous difference of pressure** between the gas in the holder and that in the mains.

When a stream is driven through a tube which is not of uniform diameter throughout, the stream **slackens** in the **wider** parts of the tube and runs **more rapidly** in the **narrower.** But the **quantity** which flows past any one point is **the same** at all parts of the stream; for if otherwise, there would be local congestion. The **pressure** is, however, **higher** where a rapidly flowing part of the stream has run into a wider space, and has been obliged to assume a **smaller velocity.**

The gas is also hotter there: for the kinetic energy of the gas as a whole is partly transformed into Heat.

If air be made to flow into a room through **conically** widening apertures, as in certain ventilating bricks, the inflow is slowed down as the air passes through : there is thus no such sharp, quick draught as would occur if the air came through simple tubes.

There are many properties of Gases, considered as masses capable of flowing in streams, which it is more convenient to consider when we come to Liquids, to which the same propositions apply : these are the Law of Continuity, Torricelli's Law, the relation between Velocity-Head and Pressure-Head, the Lateral Pressure in a stream, and the Fall of Pressure along a stream.

When gas is made to flow from a vessel through a **jet** the principle of **action and reaction** applies; the gas is driven forward from the jet, and the jet tends to be driven backwards. This we may see applied in certain revolving window-illuminating contrivances, in which the jets are so mounted that they can rotate backwards round a central axis.

The Flow of gas under a given difference of pressure is **not instantaneous**: it is measured by the **volume** which passes **per unit of time.**

According to **Barlow's Formula**, if V be the number of cubic feet which pass per hour, d the diameter of the pipe in inches, h the pressure in inches of water, s the density of the gas (that of air being reckoned as unity), and l the length of the pipe in inches, $V = 1350d^2\sqrt{hd/sl}$. Otherwise, the number of cubic cm. in time t seconds is $222{\cdot}83\, t.\sqrt{pd^5/\rho l g}$, where p is the driving pressure (that is, the difference between the full pressure applied and the pressure, if any, against which the gas is driven) in dynes per sq. cm., d is the diameter and l the length of the tube in cms., ρ is the density of the gas as compared with *water*, and g is 981, or the local number of dynes in the weight of one gramme.

In order to measure a flow of gas, the quantity of gas which flows may be actually collected in a balanced bell-jar suspended over water like a small gasholder (Hutchison's **spirometer**), or in a very large and thin flexible caoutchouc bag (Boudin) ; or it may be made to drive a registering train of wheelwork (**gas-meter**, Bonnet's **pneumatometer**).

The Velocity of the flow of air in Wind is usually measured by an **Anemometer.** This consists of a rotating vane, with little cups at the ends of its arms. These cups are caught by the wind and pushed by it: on the whole the vane rotates, and its rotation is measured by any appropriate mechanism. The rotating Torque on the vane may also be measured by the distortion of a spring, which works a dial-pointer.

An important property of streams of gas is that when they pass through other gas, while they themselves lose part of their forward momentum and are slowed, the gas through which they travel has the missing momentum imparted to it, and is as it were **dragged forward.**

A strong **jet of steam** A, driven through a cavity B and out into the outer air, will, particularly if it be directed as in Fig. 89 through a conical blow-tube, rapidly abstract a large proportion of the air in B, and tend to diminish the pressure of the gas or air in B. If there be any way by which other air can take the place of the air exhausted from the chamber B, as by the tube C, air will flow up that tube C: and if the tube C have a lower end under water, water will rise in C and fill B. When the liquid rises to the level of the steam jet A, the steam is suddenly **condensed** into liquid by passing into the water: it loses Energy thereby: this energy becomes the energy of forward momentum of the water in the blow-tube, and water is driven out with great velocity, so as even to be able to force its way against the steam-pressure in the boiler, into the boiler from which the steam itself has come. This is the principle of M. Henri **Giffard's steam injector,** for filling steam-boilers with water while working.

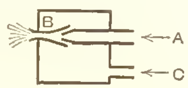


Fig. 89.

The first part of the above process is utilised in the **spray-producer.** In Fig. 90 air is driven from a bellows or two-way indiarubber ball, or steam is driven from a boiler, along a tube which terminates near the end of an outer tube B, with a conical nozzle C. The air or steam, as it rushes out at the nozzle C, carries air with it from the tube B: and this abstraction of air causes liquid to rise up the tube D, if the lower end of that tube stand in liquid, and to travel up and be hurled through C by the blast of air or steam, which breaks it up and converts it into a spray of small drops. The

Fig. 90.

same principle is applied in apparatus for blowing powders, such as iodoform or tannin.

The Pressure of the Atmosphere

The atmosphere, at the bottom of which we live, may be described as a kind of Atmospheric Ocean which, by reason of its superincumbent **weight**, exerts **pressure** upon (and at right angles to) every surface exposed to it. It penetrates into the recesses of everything porous, and *there* also it exerts Pressure, unless special appliances be made use of in order to remove it wholly or in part.

We live without inconvenience at the bottom of such a heavy atmospheric ocean, just as deep-sea fishes do at the bottom of the sea. The external pressure, about 15 lbs. per square inch, is balanced by the internal pressure of the gases contained in and dissolved within our organism ; and the force of the heart-beat and the condition of our arteries are such as to suit this external pressure.

If we go into a **diving bell**, where the air is compressed, the **drum of the ear** is pressed inwards: we must then swallow some saliva. In this action the Eustachian tube is opened, and compressed air gets to the inner side of the drum. The pressure is thus **equalised** on both sides of that membrane. The same precaution must be taken on emerging.

If we were put into a vacuum, or even into very highly rarefied air, the gases within our organism would be liberated and expand, and we would burst our blood-vessels and break up the tissues by internal effervescence. Bleeding from the nose or lungs is a well-known occurrence at high altitudes ; the walls of the blood-vessels are then not adequately supported, from without, against the internal blood-pressure.

When the air within a cavity is rarefied, the **external atmospheric pressure** will be **greater** than the internal pressure within the cavity ; and the walls of the cavity may collapse or give way, or the fact that there is an External Pressure will in some way become more marked the greater the degree of rarefaction within.

In the **Magdeburg hemispheres**, a couple of hollow bells, fitted together so as to form a sphere, are separable with ease until the air is extracted from between them: then they cannot be separated without great force.

In the boy's **sucker** the wet leather is fitted on the stone: when the string is pulled, any remaining air is expanded and rarefied, and the atmospheric pressure keeps the leather firmly pressed upon the stone.

When a **rubber disc** or **cup**, applied to a smooth surface, has its centre portion retracted by a screw acting on a piston, the same effect is observed—as in the appliances whereby **reading lamps** are attached to railway carriage windows, or **aquarium microscopes** to the glass walls of an aquarium. In other cases the same result is secured by squeezing a **rubber ball** before applying the disc or cup; the disc or cup is then firmly appressed when the rubber ball tends to re-expand, as in the attachment of **stethoscopes**, or of **surface thermometers**, to the moistened skin.

In the **feet of tree toads**, in the **suctorial discs** of Cephalopoda, in the **suctorial mouth** of Hemiptera, in the **feet** of **house-flies**, we have the same thing: this being aided in the last case by a viscid secretion, for house-flies can hold on even in the receiver of an air-pump.

In the **cupping glass** the air is rarefied, either by a rubber ball or by preliminary heating of the air within the cupping glass before it is applied to the skin. The cupping glass is then held on by atmospheric pressure; and this Atmospheric Pressure, acting on the parts of the skin not covered by the cupping glass, **squeezes** blood—or in the case of **suction nipples**, squeezes milk—into the partial vacuum.

If any object containing gas or air be placed under the bell of an air-pump, the **internal pressure** of the gas or air within the object may overpower the diminished pressure of the rarefied air surrounding it, and the object will then tend to become inflated and may even burst.

A little indiarubber **balloon**, a **bladder**, half filled with air, a shrivelled **apple**, a dish of **soapsuds**, swell up in this way. When **dry wood**, under water, is treated thus, it appears to effervesce, for its contained air expands and escapes; when the atmospheric pressure is restored, liquid is forced into the pores of the wood. An **egg** has generally an air-bubble at one end: if the opposite end of the egg be pierced, under the air-pump this bubble of air will expand and expel the other contents of the shell.

If the internal pressure at any part of our organisms become at any point less than the atmospheric, the fluids or the semi-fluid tissues or masses of the body must flow towards the region of diminished pressure. Hence a permanent **vacuum within the body**, total or partial, is **impossible**.

The **abdominal walls** are closely appressed against the viscera; and these are pressed together as compactly as their contents will allow. There is a tendency to the formation of a vacuous space between the chest walls and the lungs (the "**pleural cavity**"), but Atmospheric Pressure prevents this by dilating the lungs from within. If the chest walls be **punctured** the atmospheric pressure acts equally within and without the lungs, and they collapse.

The Pressure exerted by the Atmosphere may be **measured** by the apparatus of Fig. 87, by simply allowing the external air to enter the tube at A. This pressure is not constant, but at the sea-level it is never very much greater or very much less than a pressure corresponding to a column of **76 cm. of mercury** in that apparatus; and a pressure corresponding to a so-called "Barometric Height" of 76 cm. of mercury is called "**Standard Atmospheric Pressure.**"

This Standard Atmospheric Pressure is, per sq. cm., equal to the Weight of a column of mercury 76 cm. in height resting on each sq. cm.; that is, it is equal, on each sq. cm., to the weight of 76 cub. cm. of mercury.

This is equal to the Weight of $(76 \times 13 \cdot 596)$ cub. cm. or 1033·3 grammes of water; that is, it is 1,013663 dynes per sq. cm.

The apparatus of Fig. 87, thus used, is a simple form of atmospheric-pressure-measurer or **Barometer.**

The Aneroid Barometer, described on p. 88, is also very frequently used for determination of the atmospheric pressure.

In another form we may have a tube filled with mercury, and made to stand inverted in a vessel of mercury, with its mouth below the level of the mercury in the containing vessel. In case (*a*), Fig. 91, the mercury falls out of the tube until it stands at a height of say 76 cm., with a **vacuum** above it, the so-called **Torricellian Vacuum.** In case (*b*), where the top of the tube is exactly 76 cm.

above the level of mercury in the dish, and in case (*c*) where the tube is shorter, the mercury does not leave the tube, but continues to fill it. In all these cases the mercury tends, by reason of its Weight, to fall back into the dish, but the Atmospheric Pressure, acting on the surface of the mercury in the dish, tends to squeeze it up the tubes. The atmospheric pressure is limited, and it can support a column of 76 cm. of mercury or a column of 1033·3 cm. (over 33 feet) of water, or anything less as in case (*c*), but no more. Hence in case (*a*) there is nothing in the upper part of the tube except the inevitable **Ether** and a little **vapour of mercury.**

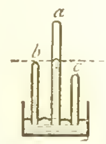


Fig. 91.

A common **water-pump** cannot act if it be so deep that during its action the Atmospheric Pressure would have to force up a column of water exceeding in height the above-mentioned 33 feet, more or less, according to the actual variations in the atmospheric pressure.

In the **mercury air-pump** a flask is filled with mercury, and is connected with a flexible tube, which is also filled with mercury, and which dips into a cistern containing mercury. If the flask be raised high enough above the cistern mercury will leave it, and a **Torricellian vacuum** will be formed in it. If the flask be connected with another flask filled, say with blood, the gases dissolved in the blood will be withdrawn and enter the vacuum-flask, which may then be disconnected for examination of these gases.

The **siphon** (Fig. 92) is a bent tube, of which one end is immersed in liquid which is to be transferred from one vessel to another, while the other end reaches a lower level B. The tube is filled with the liquid, and the end A is dipped in the tank D while the lower end B is kept closed. The tube is then opened at B, and the liquid flows out in a continuous stream, which empties the tank D down to the level of the lower end of the shorter limb. The motive power is the unbalanced **Weight** of the portion of the liquid in the siphon **between** the levels **A and B.** The preliminary filling of the siphon with liquid is somewhat troublesome; and in many cases there is, in AB, a branch

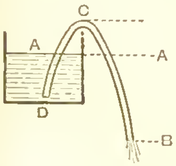


Fig. 92.

tube which is used for sucking liquid over the bend C and down the tube CB, and for thus starting the action, with the aid of a stopcock at B, which is closed during the suction.

A siphon is often used for the **automatic discharge of a tank**, which is being continuously filled with water from a tap, as in the washing of photographic plates or prints. The siphon comes **through the side** of the tank, not over its edge. Then, as soon as the water in the tank reaches the bend of the siphon, it begins to flow down CB and the action is started. But the action will not start, as a siphon action, unless the siphon tube be narrow enough to become filled at the bend C with the outflowing stream ; otherwise the liquid simply trickles over the bend C and the tank remains full. On the other hand the siphon tube must, even when at the end of its siphon action, take off a stream greater than the inflowing stream ; otherwise the tank will not, when once emptied, again become filled.

In no case can a siphon action be set up if the height AC be too great, for then a **Torricellian vacuum** is set up at the bend C ; and a siphon will not act at all under the air-pump. In ordinary cases, however, it is the **cohesion** of the liquid itself which keeps it together and makes it move as a whole.

If liquid be poured into the **stomach** by means of an indiarubber tube (whose lower end enters that viscus) and a filler, and if the indiarubber tube when full have its free end depressed below the level of the stomach, the liquid contents of the stomach will pour out through the indiarubber tube, which thus acts as a siphon ; and by this means the stomach is easily **washed out.**

A wet cloth or rag or a wet skein of thread, if left with one end in water and the other hanging over at a lower level, will act as a siphon. The siphon tubes in this case consist partly of the fibres, partly of the tough superficial film of the water itself.

Case (*c*) in Fig. 91 is illustrated by laying a card across the mouth of a tumbler completely filled with water, and inverting the whole : the card does not drop off : atmospheric pressure keeps it in position.

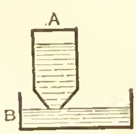


Fig. 93.

Sometimes we need a cistern for the supply of liquid to a vessel, the **level** of liquid in which is to be maintained **uniform.** Fig. 93 will serve to show how this may be obtained. A is a flask of water, filled and inverted into a dish B (also containing water), and supported at a predetermined height above B. When the liquid in B falls in the least degree below the level of the mouth of A, some liquid escapes from A, its place being taken by air which enters ; but no more liquid escapes than is requisite to block the mouth of A. Atmospheric pressure keeps the liquid in A in its place.

If the tube (*a*) of Fig. 91 be tilted obliquely, its lower end being kept immersed, the liquid will move upwards in the tube; the free vertical height remains unaltered.

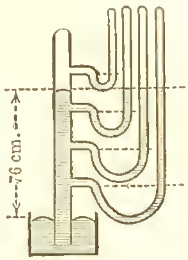


Fig. 94.

If the tube of Fig. 94, with its **lateral manometer-tubes**, be filled with mercury and inverted into mercury, the mercury in it will partly fall out if the height exceed 76 cm., and the remainder will stand as shown in the figure. The manometer fitted at the topmost part of the tube indicates, of course, no internal pressure in the Torricellian vacuum; and as we descend the tube, we find the **pressure**, as indicated by the lateral manometers, **progressively increasing**.

If we replaced the manometers by little pieces of **flexible membrane**, we should find these more bulged in at the upper part of the tube; for the differences between the internal pressure and the external atmospheric pressure are there greatest.

If an **elastic bag** be connected with a rigid cap, and if the whole be filled with liquid, the bag may, if it be of sufficient length, sag and **dilate** in its lower parts so as to form a Torricellian vacuum in the rigid cap: if it be not of sufficient length, there will be merely a diminution of pressure within the rigid cap. If the rigid cap become flexible at its upper face, it will **bulge inwards** more or less under the influence of the Atmospheric Pressure: and the form assumed by the bag will be more pear-shaped. The form assumed by the bag is determined, at each level, by the **weight** of the superjacent liquid and by the **elasticity** of the bag, together with the **atmospheric pressure**, which acts uniformly over the surface.

The atmospheric pressure is different at **different altitudes**. It is as if the air were made up of successive layers, the lower of which are **compressed** by the **weight** of those above; the upper ones are less so. The upper regions of the atmosphere are therefore, as compared with the lower ones, less dense or more rarefied, and the atmospheric pressure there is correspondingly lower because the superjacent weight is less.

Hence a Barometer (most conveniently an aneroid barometer graduated for the purpose) may be used for the approximate estimation of **mountain heights**. But in order to do this accurately it is necessary to know the **simultaneous** pressure at **sea-level**. In the lower regions of the atmosphere, near sea-level, a vertical ascent of 100 feet corresponds to a fall in the barometric pressure of about 0·29 cm., or 0·114 inch, of mercury.

The Atmospheric Pressure also **varies** at the same place from one instant to another. The atmosphere is continually undergoing local disturbances by currents, by whirlpools, by superficial waves, and by local heating, expansion, and overflow ; and all these affect the **quantity of air** which lies, for the moment, over any given spot. The **weight** of the superjacent column of air therefore varies ; and thus the local **atmospheric pressure** at any given place varies from one instant to the next.

When any spot has a low barometric pressure the air tends to **flow in** from all places where the pressure is greater. The nearer these places are the more violent is the inrush of air. The inrush is modified by the **rotation of the earth**, so that the air swirls round a centre in a direction which, in an ordinary **cyclonic** storm, is in the northern hemisphere opposed to and in the southern the same as that of the movement of the hands of a watch. In **anticyclones** this direction is reversed.

One consequence of the variations in atmospheric pressure is that we must always look at the **barometer** when we are engaged in dealing with **measurements** of the Volume of **gases**. Gases measured at the atmospheric pressure have volumes which vary inversely as that pressure; and in order to compare our experimental results we have to **reduce** all our observations of volume to the volume which would have been occupied if the gas had been measured at the **standard atmospheric pressure**, 76 cm. barometric mercury column. The older standard, 30 inches of mercury, is now practically superseded.

In many forms of **manometer** for finding the pressure of a gas, what we really ascertain is not the true Pressure within the gas, but the **excess** or **defect** of that pressure above or below the **atmospheric.**

The most common form of Manometer is a simple U-tube with **open ends.** The liquid used as a gauge comes to the same level in both limbs when the pressure in the gas is equal to that of the atmosphere : but if the pressure to be measured be greater or less than the atmospheric pressure at the time, the **difference** between the **gas-pressure** and the **atmospheric** (not the absolute value of the gas-pressure) is shown by the Difference of Level assumed by the liquid in the two limbs of the tube.

Fig. 95.

Let the student make such a U-tube and put some water in the bend ; let him connect this tube by means of a piece of indiarubber tubing with a gas-burner ; let him then open the stopcock : the water will rise so as to show a difference of level of say 1 inch or $2\frac{1}{2}$ cm. The gas is said to be supplied at "a pressure of 1 inch of water," or $2\frac{1}{2}$ cm. of water ; and this would correspond to a difference of pressure equal to the weight of $2\frac{1}{2}$ cub. cm. of water or $(2\frac{1}{2} \times 981) = 2450\frac{1}{2}$ dynes on a sq. cm. base, in favour of the gas, above the pressure of the surrounding atmosphere at the time. If at the time the barometer be standing at say 758 mm. or 75·8 cm. of mercury, the atmospheric pressure is $(75{\cdot}8 \times 13{\cdot}596 \times 981) = 1{,}010981$ dynes per sq. cm. ; and therefore the actual pressure inside the gas-pipes is $1{,}010981 + 2450 = 1{,}013431$ dynes per sq. cm.

In the tube A, which is a **compression-manometer,** there is a certain quantity of air enclosed at C by means of a certain quantity of mercury, which may be adjusted, by addition or withdrawal of mercury, so that it comes to stand at the **same level** in both limbs of the U-tube. The pressure of the air in C is then equal to the **atmospheric.** If an **additional** pressure be applied at *a* mercury will be pushed up the tube. The Pressure at *a* will be partly balanced by the **weight** of the column of mercury raised up in DE. The remainder of the pressure at *a* is spent in balancing the increased pressure of the **compressed air** in C. By preliminary graduation, that is, by ascertaining and marking at what height the mercury stands in C for various known pressures, the instrument may be made to indicate the pressures by direct reading on a scale.

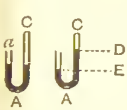


Fig. 96.

The **Bourdon steam-gauge** resembles an aneroid barometer made with a coiled tube (p. 88); but the steam is admitted to the **interior** of this tube, while the atmospheric pressure is external. Any pressure of steam greater than the atmospheric tends to straighten out the coil, and to make the tube more circular in section.

The Atmospheric Pressure acts through any mass of gas without reference to its Temperature. The air in a room may be either hot or cold: this will not, of itself, cause any difference in the atmospheric pressure within the room.

Where **local differences** are set up between the atmospheric pressure and the pressures within or external to any given object, there is a tendency to **Flow**, either of gases or of liquids or of semi-solid substances as the case may be.

The principal means of **production of differences** between the atmospheric pressure and particular local pressures are (1) the local **production** of gas; (2) **compression** of a given mass of air or gas; (3) **rarefaction** of a given quantity of air or gas.

Examples.—(1) **Production** of gas, which must either find an outlet or else accumulate in quantity and therefore in Pressure: for example, hydrogen in a hydrogen-generating flask (zinc and dilute sulphuric acid), coal gas in a **gas-retort**. The driving pressure is the **excess** above the atmospheric. In a **gas-evolution flask**, the varying Height of liquid in the **safety-funnel** measures the excess of the internal pressure above the external atmospheric pressure: that is, if the delivery tube be, directly or indirectly, open to the outer air.

(2) **Compression** of a given mass of air or gas, as in a bellows or a two-way rubber ball. In a **bellows** as used for **limelights**, the body of the bellows is filled with gas and a heavy mass is laid on the bellows: the stopcock is opened and the gas rushes out. The atmospheric pressure tends to drive air in; but the contrary tendency is the stronger: and therefore, practically, the driving pressure is the excess above the atmospheric. Similarly in the ordinary **fireside bellows**, the upper handle is raised: the air inside is rarefied: the external atmospheric pressure forces the valve underneath, and air enters the body of the bellows; the upper handle is then squeezed down, the valve falls back, and the air within is compressed; then the

air in the body of the bellows is forced out through the nozzle. In a two-way **rubber ball** there are two valves, both opening in the direction in which the air is intended to flow, and preventing back-flow ; when the ball is squeezed air escapes from the cavity through the front valve : the hind-valve is at the same time pressed back into its seat. When the pressure ceases the elastic ball strives to regain its original form. Its pressure on the contained residual air is therefore less than the atmospheric. The atmospheric pressure forces the hind-valve, while at the same time it closes the front valve. Air then flows into the ball; and the ball is free to resume its original form, which it does. The ball is again squeezed by the hand, or by the foot, and air is again driven out past the front valve.

In the **plenum** method of **ventilation** a local excess of pressure is set up by forcing air into a building : and the air is allowed to find its own way out.

When the **thoracic walls** contract **air** is driven out of the lungs, and **blood** out of the thoracic organs in general.

In **coughing** we make an expulsive effort with closed glottis, and thus produce within the chest a pressure greater than the atmospheric : we suddenly open the glottis, and air rushes out of the chest against the external atmospheric pressure.

If we connect a flask with a cistern of water situated at a height, in such a way that water can flow down into the flask from the cistern, the water will tend to compress the air in the flask, and will drive it forward through apparatus connected with the flask. This is one form of **aspirator.**

In a **gasholder,** in its simplest form, there is an inverted bell, floating in a tank of water and filled with gas. The bell is more or less **heavy** and tends to sink in the water, but it is more or less **balanced** by weights slung over pulleys. If these weights were excessive the bell would be pulled upwards, the gas would be rarefied, and the water would tend to rise in the bell ; but under ordinary conditions the bell still tends to sink, and the gas in it is somewhat **compressed,** while the water stands at a **lower level** under the bell than in the tank outside it. If this difference of level of water be 1 inch, the gas in the holder is at a pressure corresponding to "one inch of water" greater than the external atmospheric pressure. If the bell be exactly balanced, a hole may be made—provided that it be not too large—in the walls of the bell below water-level, and yet no gas will escape, for the atmospheric pressure keeps the whole in place.

In one form of **wash-bottle** we blow into a flask containing liquid, through a single nozzle : we thus compress the air in the flask. We suddenly invert the flask, and liquid is driven out in a **jet** by the compressed air within.

In the dome of the **fire engine**, air which is continuously kept compressed acts in the same way.

(3) **Exhaust-methods.**—When we remove some of the air from a confined space we have a volume of air of smaller Density, and therefore under a smaller Pressure. If, for example, we have a flask containing air at the ordinary atmospheric pressure, 76 cm. of mercury, and if we contrive to take out one-fourth the molecules, we shall have air whose density is reduced to three-fourths the original density, and whose pressure is correspondingly reduced from 76 to 57 cm. of mercury. A manometer connected with the flask would have a column of 57 cm. of mercury standing in it. We have thus made a "**partial vacuum**" in the flask. This kind of operation may be effected by means of **Air-Pumps.**

We have already mentioned the Sprengel and the Bunsen pumps. In the ordinary **air-pump** in its simplest form we have a **cylinder** A, out of which there comes a pipe B provided with a **valve** working **inwards.** In the cylinder there runs a **piston** C, through which there is an aperture protected by a **valve** working **outwards.** When the piston is thrust home, the air in the cylinder is **squeezed out** through C; none can pass the valve on B, which is pressed into its seat. When the piston is drawn back the valve on C closes, so that no atmospheric air can get in; but the air in the vessel D, which is connected with the pipe B, **expands,** lifts the valve, and fills both D and the expanding cylinder. On thrusting the piston home again a part of this air is **driven out** through C. This operation is repeated until a considerable proportion of the air in D has been extracted. It becomes more and more difficult to pull the piston back, as the difference between the internal pressure and the external atmospheric pressure goes on increasing.

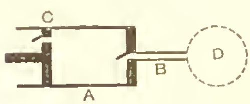


Fig. 97.

If we run a **roller** along a long **rubber tube** which is connected with a flask, we squeeze air out in front of the roller, and air from the flask follows the roller up as the rubber tube regains its form. A second roller, following the first, will again drive out some of this air; and so on. On this principle apparatus has been made in which a single roller acts successively upon different parts of one and the same rubber tube coiled inside a **drum**: and on rotating the drum, air is continuously withdrawn from a flask or bell. The rubber **tube** must be yielding enough to be **perfectly closed** by the squeeze of the roller, and at the same time elastic enough to **regain its form** when the squeeze is over, in spite of the external atmospheric pressure which tends to make it collapse.

"**Suction.**"—Suppose we have a closed tube containing some air or gas, standing in mercury as shown in Fig. 98, with the mercury at the same level inside and outside the tube: the gas in A is at a pressure equal to the external atmospheric pressure. Let us now pull the tube up somewhat; two things happen: the **gas expands** and is rarefied, and the **mercury ascends** somewhat in the tube. The ascent of the mercury and the expansion of the gas bear a necessary relation to one another. This may be illustrated numerically.

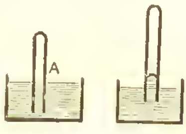


Fig. 98.

Let the external atmospheric pressure be that of 76 cm. of mercury; let the mercury rise 10 cm. in the tube: then the pressure inside the tube, above the mercury, corresponds to a mercury column of 66 cm.: and the gas, being subjected to this pressure, must, by Boyle's Law, have expanded to a volume equal to $\frac{76}{66}$ times its volume at the atmospheric pressure. This **expansion** of volume and the corresponding **ascent** of mercury in the tube, **adjust themselves** to one another at every instant while the tube is being raised. Thus the gas is rarefied, and the Atmospheric Pressure **pushes** mercury up the tube after it. It comes to the same thing if we have a **cylinder** with a **piston**: pulling up the piston makes the gas follow the piston: the gas is rarefied, and the liquid is pushed up after it by the Atmospheric Pressure. This is applied in the ordinary and well-known **Syringe.**

In the **common pump** a device is added for preventing back-flow, and for thus taking advantage of the ascent of the liquid column, when the object in view is the raising of liquids. In this instrument the **piston** P (Fig. 99, there represented, for the sake of simplicity, without the rod by means of which it is moved up and down) is so made that fluids can **flow upwards through it**; but if they tend to flow back through it, a **valve** (say a clapper-valve, or a ball resting in a cone) closes, and prevents their return. As the piston is raised the air underneath it is rarefied; the atmospheric pressure closes the valve; and water from the well W follows the ascending piston, being **pressed up** into the cylinder by the **atmospheric pressure.** As the piston is sharply returned, some of the **air** beneath the piston **escapes** upwards through the valve. As the piston is again raised the **water** is again raised, this time to a **higher**

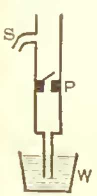


Fig. 99.

level; and more air escapes at the next return of the piston. So on; at length there is so little air left that on its return the valved-piston dips into the water and some water comes up above the valve. When the piston is next raised it lifts that water bodily, and allows it to flow out at the spout S. At the next return more water passes through the valve, again to be poured out at S; and so on. If the column of water to be lifted exceeds about 33 feet in height, the utmost that could follow would be the production of a Torricellian vacuum; the pump will fail to lift water to the piston, because the Atmospheric Pressure could not push it up so high.

In the force-pump this inconvenience is obviated by another arrangement of valves and pipes. The working piston P is quite near the water to be pumped up. The water comes up as in the ordinary pump, but it does not flow through the piston, which is solid. It is forced by the descent of the piston through an outward-acting valve into a lateral chamber and tube, and it cannot return against that valve. If the valves and pipes be strong enough, water may by this means be lifted to considerable heights.

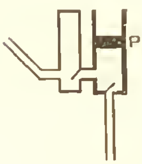


Fig. 100.

If an aspirator (a form of syringe) for withdrawing pus from an abscess be worked too hard, the pressure within the abscess-cavity may be too far reduced. The external atmospheric pressure, acting through the surrounding tissues, may then burst blood-vessels, and the aspirator may fill with blood instead of with pus alone.

When a liquid is imbibed through a straw, the mouth-muscles make a partial vacuum, and atmospheric pressure pushes the liquid up from the tumbler into the mouth.

In a pipette, with a rubber cap, the expansion of the rubber tends to produce a partial vacuum, and the liquid runs up to a height where the Weight of the liquid *plus* the partial Pressure above the liquid are in equilibrium with the external Atmospheric Pressure *plus* the surface-tension of the curved upper surface, which is itself able to support a certain height of liquid column.

When we take a breath we expand the chest and depress the diaphragm. The air in the lungs tends to become rarefied; but the atmospheric pressure pushes air into the lungs, down the trachea and bronchi.

If a great vein be cut the atmospheric pressure may drive air into the vein at each inspiration.

When a drowning man gasps for breath under water, the atmospheric pressure may, in the same way, push mud, leaves, etc., along with water into his respiratory tract.

If the lungs breathe into rarefied air the chest-walls are forcibly squeezed together by the atmospheric pressure.

When the bones of a **joint** are separated by extreme flexion, the atmospheric pressure tends to drive skin and tissues inwards, and thus make an external dimple.

If a **test-tube** be nested into a slightly larger one containing water, it will float. If the whole be inverted, as the water escapes the smaller tube will be **pushed up** into the larger by atmospheric pressure.

In the **vacuum** method of **ventilation** air is expelled from the building by a fan: air is pushed in, by the atmospheric pressure, to take its place. Exhaustion by a fan is applied in the **exhaust** at gasworks, in the **ventilating fan** of a coal mine, in the **smoke-jack** of a chimney.

If the air in a room be **rarefied** by a strong **chimney-draught**, the atmospheric pressure acting through the drains may be able to **force the trap** of a toilet-basin.

In **aspirators** for drawing air through chemical apparatus, water is allowed to flow out of a large jar; air must take its place, else the air within the apparatus will be rarefied; and this fresh supply of air is pushed by the atmospheric pressure through the apparatus, along which a path has been provided for it.

Dr. Braun of St. Louis has revived babies asphyxiated at birth by fitting them in a box with an aperture exactly fitting the face. The mouth and nose are thus exposed to atmospheric pressure; the body is in the box. On rarefying air in the box, air is driven into the lungs by the atmospheric pressure: on compressing it the chest walls are squeezed and air is expelled. **Artificial respiration** is thus set up.

In all these cases the Driving Pressure is the difference between the actual local pressure and the general atmospheric pressure.

It comes to the same thing, mechanically, whether the driving pressure be due to the one or the other of these causes; the only difference is that by **compression** we may attain **any driving pressure** we please, while with **exhaustion** we cannot possibly attain a driving pressure greater than the full **atmospheric pressure** itself.

For example, if we promote **filtration** by connecting the flask A with a Sprengel or Bunsen air-pump, we may make the atmospheric pressure, or any desired fraction thereof, drive the liquid through the filter-paper into the flask A; but if we were to enclose the funnel within a casing (Fig. 102) and drive air into that casing from a bellows or rubber ball, we could make the compressed air within the casing drive the liquid through the filter-paper into the outer air at any desired pressure.

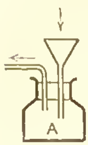


Fig. 101.

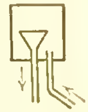


Fig. 102.

Anomalies in Ordinary Gases

In Gases, as we usually have them at ordinary temperatures and pressures, the Molecules come within the range of one another's attractions; and this interferes with the relative movements of the molecules; so that our ordinary Gases are not "perfect gases."

Consequently Boyle's Law is only approximately obeyed; the product of the pressure into the volume tends to become too small as the pressure increases; that is to say, the Volume diminishes, with increasing pressures, more rapidly than the law would indicate: and this departure from Boyle's Law is more marked the nearer the Temperature at which liquefaction or condensation occurs. Again, the lower the temperature the more marked are the departures from Boyle's Law; but the hotter the gas the more nearly it acts as a "perfect gas."

Again, the coefficient of expansion by heat is, at high pressures, in most cases higher than the law previously given would indicate.

When we mix two quantities of different gases at different temperatures, there is in many cases a tendency to the resultant temperature being higher than the theoretical mean; for there has been liberation of Energy through the satisfaction of mutual affinities between the molecules of different kinds. There is also a tendency to Volumes smaller than the sum of the component volumes, and to Pressures smaller than Dalton's Law would indicate.

When gases are allowed to undergo mere expansion, without doing work, the Temperature is not quite as high after the expansion as it was before it; and this circumstance has been used by Lord Kelvin and Mr. Joule to prove that Energy is consumed when gases expand, and that therefore no actual gases are "perfect." It is as if the molecules attracted one another, and **work** had to be expended in pulling them apart. In **hydrogen**, curiously, the molecules seem to repel one another ; for Energy is given out when the gas expands.

The **thermal capacities** of ordinary gases at constant pressure and at constant volume respectively are not in the ratio $1 \cdot 66\dot{6}$ to 1. The ratio is smaller than this ; and the actual value of each Thermal Capacity is greater than it would have been in a "perfect gas." This is because a varying and sometimes a very large amount of Energy is used up in overcoming intermolecular forces.

The speed of **propagation of vibration** in actual gases is not as great as it would theoretically be in a perfect gas ; but it approximates to the theoretical value as the gas is rarefied or becomes hotter.

The Critical State and Liquefaction

As a Gas becomes more and more compressed, its Molecules approach one another more and more nearly ; and they are more and more hampered by one another in their movements. As the compression goes on a time comes when the gaseous properties of the substance are lost, and the gas is compressed into a **liquid**. The hotter the gas is the more difficult it is to compress it into a liquid; and for every Gas there is a particular temperature, the **Critical Temperature**, beyond which no amount of compression can reduce it to a liquid ; though compressed into a very small bulk the gas remains a gas, if its temperature be above that limit. For example, for carbonic acid gas, CO_2, the critical temperature is 30°·92 C. ; and above 30°·92 C. carbonic acid gas cannot be liquefied by any amount of pressure. Below 30°·92 C. a sufficient pressure will liquefy it. The pressure which will liquefy it at 30°·92 C. is 73 atmospheres ; and this is called the **Critical Pressure**. At temperatures below 30°·92 C. smaller pressures will liquefy the gas.

If our ordinary temperatures had been above 30°·92 C., we would have said that carbonic acid gas was a gas which could not be liquefied by any degree of pressure alone, and that in order to liquefy it we must **cool** as well as **compress** it. Our **ordinary gases,** such as hydrogen, oxygen, and nitrogen, are in this position, for their **critical temperatures** are **extremely low** (oxygen − 118° C.); and we must cool them below these temperatures before we can condense them by pressure, which, in such cases, has to be very great. Hence we have usually to apply both Pressure and Cold in order to condense gases into liquids. In other cases, however, pressure alone at ordinary temperatures, or cold alone at ordinary pressures, will condense the gas into a liquid; and if a substance which is a gas when it is hot or rarefied becomes liquid under **ordinary pressures** at **ordinary temperatures,** as steam does when it condenses into water, we say that the gas is the **vapour** of the liquid. The Liquid is then the more ordinary or familiar form or state of that substance.

Steam, as it is usually formed, is an imperfect gas, for it is near its condensing temperature: but if we rarefy it or make it very hot it comes to act more like a perfect gas. The critical temperature of steam is as high as 720°·6 C.

If we heat a certain bulk of a liquid to its Critical Temperature without allowing it to expand, it becomes a gas or vapour without any change of state being apparent.

LIQUIDS

The Molecules of an ordinary Liquid being crowded together more than they usually are in a Gas, liquids are denser than gases; and the **Density** of Liquids varies from that of liquefied acetylene, which weighs 0·34 gramme per cubic cm., to that of mercury, which weighs 15·596 grammes per cub. cm. at 0° C. Water weighs 1 gramme per cub. cm., human blood from 1·045 to 1·075 (average 1·055; abnormally, as in chlorosis, 1·030), sulphuric acid about 1·875; and one of the heaviest ordinary liquids is a solution of iodide of mercury with iodide of potassium in a minimum of water, which has a density over three times that of water. This solution is an exceedingly powerful corrosive of the skin. A mixture of equal parts of nitrate of thallium and nitrate of silver, fused at 75° C., has a density of 4·5, and is miscible in all proportions with water.

Lighter particles rise in a heavier fluid, *e.g.* cream in milk.

In Liquids the Molecules are so near one another that they have **hardly any free path**, but they retain a power of **slipping past** one another. The consequence of this is that a Liquid can **flow**; it is a **Fluid** as distinguished from a Solid.

Liquids can, accordingly, **assume any form** which may be imposed upon them by the surrounding conditions, but do **not** do this **instantaneously.** If we tilt up one side of a dish of treacle, the treacle takes more time to come to a level than water would, and water more time than ether ($C_4H_{10}O$); and the ether would oscillate more in the dish than the treacle will. The treacle flows with more difficulty than the water, that is to say, it is more "viscous." The **Viscosity** of a liquid retards the Flow of a liquid; and the more viscous a liquid is, the more **time** will it take to flow through a **capillary tube** under given conditions.

Given sufficient time, however, all true Liquids will ultimately assume the same form, and will fill the recesses of any vessel of irregular form in which they may happen to be placed.

Melted iron, being somewhat viscous, will take a sharper impression on casting if it be subjected to pressure while in the melted condition in the mould; it is thus made to fill all the interstices before any outer hard skin has formed.

If a body **vibrate** within a liquid,—if, for example, a bell be rung under water,—the vibrating body produces alternating **Compressions** and **Rarefactions** in the water, and these are propagated through the water by a

Wave-Motion. The **viscosity** of the liquid affects the **speed of propagation**, slightly reducing it; and the viscosity has the further effect of gradually transforming the Energy of Wave-Motion into **Heat**, so that the wave-motion itself dies away.

Liquids are more **resistant to rapid motion** through them than to slow; the Friction increases with the speed. When the motion is rapid the liquid does not readily move out of the way, while when it is **slow** the liquid **flows round** to the back of the moving object. Thus Ctenophora move about by more swiftly bending and more slowly straightening the hair-like **cilia** which are arranged in bands on their surface; and spermatozoa travel by lashing a single cilium, somewhat after the fashion in which an oarsman sculls a boat. The rapid rotation of an Archimedean Screw or a **screw-propeller** is resisted by the water, which tends to damp the motion; but conversely, if the water be in motion the wheel will be set in motion, as in the **turbine**.

To the same Intermolecular Forces which cause Viscosity the **Cohesion** of Liquids is due. It is always somewhat difficult to break a column or stream of liquid, as in the Siphon, Fig. 92, where the liquid does not part asunder at C, but moves as a whole. And it is even possible to set up a certain amount of **rarefaction** in a Liquid, so that the lateral manometric pressure may be less than zero, the stream or column being then under a certain amount of **tension**. A drop of liquid suspended on a glass rod may be increased up to a certain size before it breaks off.

If a liquid be **compressed, work** is done against the Intermolecular Forces: and these intermolecular forces are considerable, as is shown by the very small **Compressibility** of liquids, that is, their very small shrinkage under the application of compressing Forces.

If we had a cylinder of water, with a transverse sectional area of 1 sq. cm., and if we were to apply a Force or Pressure of one dyne (per sq. cm.) to the free surface by means of a piston, the Volume would shrink by $\frac{1}{20700.000000}$ of its amount; if we applied the weight of a gramme the shrinkage would be $\frac{981}{20700.000} = \frac{1}{21.100000}$ of the original volume; if we applied one atmosphere pressure (=1,013663 dynes) the shrinkage would be $\frac{1013663}{20700,000000}=\frac{1}{20400}$. **Water** is therefore **compressible** to the extent of $\frac{1}{20400}$ of its volume per atmosphere pressure.

The shrinkage is, for moderate pressures, **proportional to the pressure**; but in the case of water it is so small, that for many practical purposes **water** may be treated *as if* it were **incompressible.** When the compressing Pressure on a liquid is relaxed, the liquid perfectly regains its original Volume; whence it is said that the **Elasticity of Volume** of a Liquid is **perfect.**

Liquids generally **expand when heated**; and the Coefficient of Expansion by Heat (the **ratio** between the **expansion** per degree Centigrade and the original **volume**) varies slightly, but very slightly, with the temperature; so that on the whole the Expansion or dilatation is **proportional** to the **rise of temperature.** Conversely, there is a shrinkage or contraction proportional to any fall of temperature.

A full kettle of water will thus overflow when heated.

It is a fortunate circumstance, in view of the needs of the thermometer-maker, that the Coefficient of Expansion of **mercury** is, between $-36°$ C. and $100°$ C., almost uniform, being, for each °C., $\frac{1}{5555}$ of its volume at 0° C. This enables the **degrees** on the scale of an ordinary **thermometer** to be made **uniform** in size; but above 100° C. the expansion becomes more rapid, and above that temperature the scale ought, for extreme accuracy, to be specially graduated by comparison with an air-thermometer.

When a liquid is heated, as it expands it becomes **lighter**; and when a lamp is lit under a vessel of water, the parts of the water nearer the lamp-flame become lighter: then the **cooler** portions of the water, being heavier, **fall** to the bottom. The **heated** portions of the water thus **rise** to the top, and the portion exposed to the heat is constantly being renewed. The currents thus induced in the water are called **convection-currents.**

When the Temperature falls back to its original value a liquid perfectly regains its original Volume.

Below 3°·9 C. **water** *contracts* when it is heated; so that water has a **maximum density** at that temperature. Water is in this respect an exception to the general rule. This retards the freezing of lakes, for the coldest part of the water rises to the top, and lies there.

Free Surface.—A liquid, placed in a vessel which it does not entirely fill, has a **free surface**: and this surface is usually **level**, at right angles to the direction of the Force of Gravity.

Whether level or not, it is always at right angles to the Resultant of the Forces acting upon it. For example, if we whirl liquid in a vessel, the forces acting at any point are (1) the force of **gravity** acting downwards; and (2) **centrifugal** force acting outwards: the resultant of these is inclined to the vertical: and the surface of the rotating liquid is therefore sloped. The slope varies from point to point, so that the whole surface of the rotating liquid assumes the form of a "**paraboloid.**"

The Form of the Surface of a Liquid is also affected by **Surface Tension**, which may now be explained.

Any molecule in the interior of a drop of liquid is **equally** acted upon **on all sides** by the neighbouring molecules; and, consequently, it is not pulled by them in any one direction more than in any other. But a molecule at the **surface** is pulled upon **only** by molecules **internal** to it, while there is nothing to compensate this attraction. The consequence is that each and every superficial molecule is pulled in towards the bulk of the liquid. All the superficial molecules, therefore, get as near as they can to the centre of the mass of the drop. The **surface** of the drop thus tends to assume the **least possible area** consistent with the quantity of liquid in the drop. It is as if the superficial layer itself formed a **superficial film** or **skin**, which was always under **Tension**, and which endeavoured at all times to mould itself into the least possible Area consistent with the existing conditions. This surface-film is as it were **elastic**; and mercury globules can rebound when thrown on the table.

As an example of this we may take the free surface of water standing in a glass vessel. We find, if the glass be clean, that the water is not flat over the whole of its surface, but rises up round the rim, as may be seen in a tumbler of water.

This is because we have to do with **three surfaces**, (1) the surface between water and air, (2) that between water and glass, and (3) that between glass and air. Along all these surfaces, even the last, there is a **superficial tension**; and the resultant of these three tensions is such that the **rim** of the water tends to be **pulled up** the clean glass in a thin layer.

The surface-film of the water being thus pulled out of shape, the form of the water has to follow this distortion of the surface-film.

If we dip a **capillary tube**—as, for instance, an ordinary vaccine-lymph tube—into water, we observe two things: (1) the **upper surface** of the water is **deeply curved**, for the surface is as it were all rim and no flat; and (2) the pull upon the rim **pulls water** bodily **up the tube** until the downward Weight of the water pulled up balances the upward Pull on the rim. This pull of the liquid up the tube is what is called **capillary attraction.**

The pull upon the rim, due to the Surface-tension, thus determines the **height** to which the liquid will rise in a **capillary tube**; but it will be noticed that this is a phenomenon which does not present itself unless the liquid have a **free surface.**

It is vain to attempt to explain the rise of liquids in capillary tubes, as in the vessels of plants, by this "capillary attraction" unless there be a free surface. There may, however, be "capillary attraction" in another sense: this is illustrated by the rise of oil, pushing up water, in an oily capillary tube: the walls of the oiled tube have a greater attraction for the oil than they have for the water. When we put a **porous** object, such as a lamp-wick or a lump of sugar, into water, the pores become filled by the ascent of the liquid in them. This process, which is called **imbibition**, may be partly due to capillary attraction in the one sense, partly to capillary attraction in the other. A wetted rope becomes warm, partly because the attraction between rope and water is satisfied, partly because of the concurrent shrinkage. The flow through a lampwick will not be continuous unless the liquid be continuously removed above.

We also see imbibition where moisture travels from brick to brick from damp soil, where there is no "damp course" or impervious layer of slate to prevent this, and in the cases of lint, of absorptive cotton, and of starch and other drying powders.

In ordinary cases, where a mixture of oils of different volatilities is imbibed by the lampwick of an unlit lamp, the more volatile evaporates away the more rapidly, and in course of time the mixture in the reservoir becomes denser; but where the flame is lit and the wickholder is hot, the whole oils, if none of them be too heavy, are evaporated together, each at the point where it finds an appropriate temperature, and the oil in the reservoir does not vary in its composition.

The height to which the liquid can rise in a capillary tube varies inversely as the diameter of the tube. If we double the diameter we double the length of the rim, and we therefore double the mass of water which can be lifted by it; but this double mass, it will be found, will stand only at one-half the original height in the wider tube.

In a tube we may equally well say that the actual Curvature of the superficial film, which film always tends to be flat, can only be maintained by suspending upon that tough or elastic surface film a certain mass of heavy liquid.

Between two plates the height is half what it is in a tube, whose diameter is the same as the distance between the plates: and if two flat pieces of glass be dipped in water, with one vertical edge of each in contact with a vertical edge of the other, the water stands between them at such heights that its free edge presents the form of a curve known as an equilateral hyperbola.

When water is drawn up into a pipette, or an animalcule dipping-tube, and the whole pipette is freely exposed to the atmosphere, it will be found that a certain quantity of water tends to remain in the pipette, supported by the surface tension of its upper free surface, while the more sharply-curved and smaller lower surface tends to pull the liquid down towards the point of the pipette.

The pull exerted by the curved surface of a liquid may also be seen when we lay a cover-glass upon a microscopic slide, and lead a drop of water up to the edge of the cover-glass: the water is pulled in between the slide and the cover-glass, and there spreads.

In the case of mercury in glass, the resultant of the surface-tension is such as to make the mercury stand, as may be seen in a glass bottle or tube containing mercury, with a surface convex upwards, the pull on the mercury-rim being in this case downwards. The effect of this is the converse of that observed in the case of water. Mercury, therefore, sinks in a capillary glass tube.

In the same way the amount of depression of the surface of mercury is, in capillary glass tubes, inversely proportional to the Diameter of the tube. This circumstance necessitates the application of a correction to the readings of manometers, barometers, and the like, in which the height of a mercury column is observed.

The correction for capillarity depends on the kind of glass, and is not the same in all barometers; so that the correction depends not only on the diameter of the tube, but also on the actual convexity of the surface.

A piece of camphor flies about when laid on clean water. This is because the portions of the surface which happen to have dissolved most camphor have least superficial tension and pull least upon the floating lump: it is therefore pulled in the direction of the least camphoraceous portion of the surface. But if the finger, with a trace of grease on it, touch the surface of the water, this effect will not be produced: for the surface-tension of the water is greatly reduced by this. If the vapour of ether be poured upon the water the surface-tension will be reduced in the same way. If a drop of alcohol be laid on a film of water, the water will pull itself away from the alcohol, for its surface-tension is greater than that of alcohol. Weak spirit has greater surface-tension than strong: hence, if a quantity of strong wine in a glass be tilted so as to moisten the sides of the glass, the film left will lose some alcohol by evaporation, and will then pull itself up the sides of the glass. Cold water has more surface-tension than hot; hence, if we heat one point in a film of water, the water withdraws to the edges of the film.

Surface-tension not only pulls water up against glass, but pulls glass down in water. A floating hydrometer thus sinks too deeply in the liquid, so that the liquid appears lighter than it really is. If it be at all greasy the hydrometer is repelled and stands too high; but if the water be greasy and the hydrometer clean, the hydrometer stands more nearly at a proper level.

The contraction of a superficial film is manifested, in an inverse fashion, in the globular form which a

bubble of gas in a liquid tends to assume. The bounding surface of the bubble assumes the smallest possible area.

The general proposition, that a contracting film tends to assume a globular form, is illustrated by any hollow contractile viscus of the human body, which tends to assume such a globular form when it contracts.

The superficial film of many liquids presents, after exposure for some time to the air, considerable **toughness**, which in some solutions is very well marked.

A solution of saponine (from quillaia bark) or of soap will permit an ascending bubble to **tear off** the superficial film, which the upward pressure and the surface-tension are not able to rip up. Not only, therefore, can the soap-water or the saponine solution form **froth** when shaken, but **bubbles** can be blown with them. Solutions of albumen or gum arabic will froth, but bubbles cannot be blown with them. Pure, perfectly clean water has no superficial viscosity, and will therefore neither froth nor form bubbles. Alcohol has a surface film less tough than the liquid itself: hence the addition of alcohol reduces the superficial film-toughness of a liquid; and for this reason spirit is of service in **checking frothing** in pharmaceutical operations.

The toughness of the superficial film accounts for the **floating of scum** on water, for the floating of an **oiled needle**, for the **walking** of an **insect** on water.

When **oil** is poured on **troubled water** the oil spreads into a layer, for the surface-tension at the edge of the oil pulls it continuously outwards. The new oily surface has little surface-tension and much toughness, and is therefore not readily broken up into surf.

When a **bubble bursts**, it bursts explosively: it projects its own substance and the contained gas some three or four feet through the air. This occurs during the effervescence of fermenting sewage.

Solution in Liquids.—If we pass a Gas into a Liquid, a certain volume of the gas will generally be **dissolved** by the liquid. In the resultant Solution the **molecules** of the gas are **disseminated** among those of the liquid. The solubility of different gases in the same liquid and that of the same gases in different liquids varies very greatly: one cubic cm. of water will, at 0° C., dissolve

1148 cub. cm. of ammonia gas, but will dissolve only 0·0325 cub. cm. of oxygen. The "**solubility**" of these gases in water is accordingly said to be 1148 and 0·0325 respectively.

The solution of a gas in a liquid is generally greater in volume than the original liquid used.

The **higher the temperature**, the **less** in general is the **solubility** of any Gas: the gas-molecules in the solution escape from the surrounding molecules of the solvent: and therefore if the solution be heated the gas will leave it. In some cases, however, the gas does not simply leave the solution upon heating: for example, on heating a solution of hydrochloric acid gas in water, hydrochloric acid gas is at first given off, until a certain degree of dilution is reached; and after reaching this limit the dilute hydrochloric acid solution distils over bodily.

Diminution of pressure, again, enables dissolved gases in many cases to leave their solvent: ammonia solution, for example, gives up its ammonia as gas when under the air-pump; but hydrochloric acid will not give up more than a portion of it in this way.

We may regard such a solution as that of hydrochloric acid gas in water as being in some respects analogous to a Chemical Compound; and then we bring this behaviour of hydrochloric acid solution into line with that of a solution of bicarbonate of soda, which somewhat suddenly gives off half its carbonic acid when the pressure is greatly reduced. When **blood** is exposed to continuously diminishing pressure, it first gives off such carbonic acid and oxygen as it may happen to hold in simple **solution** (about ½ per cent by volume), and then, at a very low pressure, it begins to give off, somewhat rapidly, the carbonic acid and the oxygen which it had held in feeble **chemical combination** with its serum and with the hæmoglobin of its blood corpuscles respectively. If the pressure be sufficiently reduced these gases will be entirely given off. Carbonic oxide absorbed by the red-blood corpuscles will not be given off in this way, nor will hydrocyanic acid.

At an **altitude** of some 17,000 feet the pressure falls to 30 cm. of mercury: and at this pressure the **blood** begins to **give off** the **gases** which it holds in solution and in combination with hæmoglobin. This is dangerous, for bubbles of these gases, liberated in the blood-vessels, tend to interfere with the valves of the heart and to obstruct the circulation in the small blood-vessels. In a **diving bell** more of these gases are dissolved in the blood than can be retained at ordinary atmospheric pressure; and a similar risk of gas being liberated in the blood-vessels is encountered on **emerging**, unless the pressure be reduced gradually. If any untoward symptoms arise the patient should be at once re-exposed to the high pressure: the liberated gases will then be redissolved by the blood.

In many cases the Quantity, that is, the number of grammes, of a **gas** which is **dissolved** by a given volume of a liquid is directly **proportional to the Pressure**: thus at five atmospheres' pressure water will dissolve five times as many grammes of carbonic acid as it will do at one atmosphere pressure; that is to say, it will always dissolve the same Volume of the gas at all Pressures. This is **Henry's Law**. This law is interfered with if there be any chemical combination between the solvent and the gas dissolved, or when the solubility of the gas in the liquid is very great.

The **air respired by fishes** is the **air dissolved** in the water; and as the atmospheric air is made up of oxygen 20·9, nitrogen 78·28, and argon 0·82 per cent by volume, gases whose respective solubilities are 0·03250, 0·01607, and 0·0394, the composition of the air dissolved is oxygen $20{\cdot}8 \times 0{\cdot}03250 = 0{\cdot}676$; nitrogen $78{\cdot}28 \times 0{\cdot}01607 = 1{\cdot}258$; and argon $0{\cdot}82 \times 0{\cdot}0394 = 0{\cdot}0323$; or oxygen 34·38, nitrogen 63·98, and argon 1·64 per cent by volume.

Mutual Solution of Liquids.—If we pass **alcohol vapour** into cold **water** it will condense and **dissolve** in the water; and the same result will be reached if we add an equivalent amount of **liquid alcohol** to water. In such a case there is some evolution of Heat and a concurrent shrinkage of volume: while in some cases (*e.g.*, alcohol and bisulphide of carbon) there is an expansion and a concurrent cooling. Some pairs of liquids are therefore **mutually soluble**. In other cases, as **oil**

and water, the liquids will not mix. In others, again, as in the case of **ether** ($C_4H_{10}O$) and **water** they will mix in certain proportions; water will dissolve a little ether, and ether will dissolve a little water; but if say equal parts of ether and water be put into a bottle and shaken, they will separate into two layers,—the one a saturated aqueous solution of ether, the other a saturated solution of water in ether.

Diffusion.—The power which the particles of a Liquid retain of **slipping past** one another, though their free path is extremely restricted, is manifested in the phenomena of **Diffusion**, which may be best studied in solutions of salts or other solid substances. If a phial filled with a saline solution be wholly immersed some half an inch under water and left to itself, the salt will slowly diffuse out of the phial into the surrounding water. The amount of the salt which leaves the phial will depend on the length of Time, on the Strength of the solution, and on the Temperature; and it will also depend on the **kind** of salt or **substance dissolved.**

Other things being equal, urea and common salt leave the phial twice as fast as sugar, four times as fast as gum arabic, and more than eight times as fast as egg-albumen.

If it take a given weight of hydrochloric acid one day to travel a certain distance in a column of water, it will take an equal weight of common salt $2\frac{1}{3}$ days; sugar, 7; sulphate of magnesia, 7; albumen, 49; and caramel, 98 days.

If a **mixture** of salts be treated in this way, each salt diffuses out of the phial almost independently of the others, and at its own rate of diffusion.

If a **double salt** be used, it is often found that there is chemical decomposition; from alum, sulphate of potash and sulphate of alumina diffuse out, each at its own rate.

Substances which diffuse slowly or not at all are mostly amorphous or glue-like; *e.g.*, jelly, glue, caramel. Substances which diffuse rapidly are mostly crystalline. The former are called **colloids**; the latter **crystalloids.**

Colloids have probably **large molecules** made up of large numbers of atoms; *e.g.*, protoplasm, which has more than

30,000 atoms per molecule. Crystalloids have simpler molecules, with fewer atoms; *e.g.*, common salt.

Colloids are often in a state of **unstable molecular equilibrium**, and are ready to decompose when in a moist condition.

Colloids are very **tenacious** and adhere firmly to other colloids; *e.g.*, isinglass to glass.

Colloids can often have their **moisture replaced** by alcohol or olein. An animal tissue is in great part made up of colloids; and by repeated washing in alcohol it can have its moisture expelled and replaced by alcohol.

Colloids, being very slightly diffusible, are **tasteless**: they do not reach the nerve-ends. For the same reason they are very **indigestible**—*e.g.* gelatine—unless peptonised; peptones being, by exception, diffusible, though otherwise colloidal.

Hæmoglobin, from the red-blood corpuscles, has a crystalline form though it is otherwise colloidal.

If a layer of pure jelly be laid on a layer of jelly containing salts, the salts will diffuse into the pure jelly. Were it not for this diffusion of salts through jelly it would not be possible to wash photographic gelatine plates.

Osmosis.—If a layer of **colloid** matter be laid between pure water and a solution containing both Colloids and diffusible Crystalloids, the latter will gradually **pass through** the colloid septum, while the former, the colloids, will not.

If a membrane or film of a colloid substance be laid between two different liquids, and if that layer or membrane or film be more readily **wetted** or soaked by one of the liquids than by the other, the wetting liquid will gradually travel through the wetted colloid septum or partition, while the reverse passage of the other liquid is barred. If alcohol and water be separated by a thin layer of **indiarubber**, the alcohol will travel into the water; if by an **organic** septum, such as an animal membrane, the water travels into the alcohol. If hydrochloric acid solution and water be separated by an animal membrane, both liquids wet the septum; the hydrochloric acid is, however, more attracted by the septum than the water is, and more hydrochloric acid passes through in the one direction than water in the other.

If a **weaker** and a **stronger** aqueous solution of the same crystalloid substance be thus separated by a colloid septum, and if the colloid septum be permeable to water but not to the dissolved substance (*e.g.* if it be a film of ferrocyanide of copper, such as is produced by bringing a solution of copper into contact with one of a ferrocyanide), **water will travel** through the septum until the strength of the solution is **equalised** throughout ; this is the process of **Osmosis** properly so called.

Let the arrangement be that of Fig. 103, in which the solution is contained in a flask, while the water is contained in a jar surrounding it, and the solution and the water are separated by a ferrocyanide film C, impermeable to the crystalloid itself: and let the two liquids have at first the same level E: the water will flow through the ferrocyanide film into the solution until the liquid in D has attained a certain **height.** When that height has been attained, the liquid in A has become exposed to a certain **additional pressure.** When the additional pressure has been attained in A, **no more** molecules of **water** come through B. The pressure in question is called the **Osmotic Pressure** of the solution in A. It keeps out any further molecules of water, and balances any tendency they may have to permeate the membrane. This pressure is due to the molecules of the dissolved substance in A, and is measured by the difference between the level of liquid in D and that at E. Very curiously, this pressure is always **proportional to the number of molecules** of the crystalloid in A, and varies directly as the **absolute temperature.** That is to say, this Pressure obeys the **laws of gaseous pressure,** and the crystalloid dissolved in A acts in every respect as if it were a **gas,** entirely independent of the liquid throughout which its molecules are disseminated.

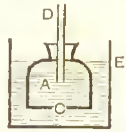


Fig. 103.

Sometimes the Osmotic Pressure is too great for the number of molecules of the crystalloid which can be supposed to be present: but a general comparative survey shows us that this may be accounted for by inferring that whereas such a crystalloid as sugar does not decompose upon solution in water, the **molecules,** for example, of common salt are **split up** into atoms or "**ions**" of Na and Cl which float independently in the water, but recombine to form crystalline chloride of sodium when the water evaporates away.

The same name, Osmosis, is also given to transferences of molecules in similar apparatus, through **membranes** which are appreciably **porous.** In such a membrane the process involves **streams** of molecules **in each direction** through the pores; and this goes on until the solution on both sides of the membrane (generally an animal membrane or parchment paper) becomes uniform.

Oil globules of extreme smallness, floating in water, tend more readily to pass bodily through the pores of animal membranes if some alkali be mixed with the water; for then they have each a soapy covering, and are not repelled by the moist membrane, but travel, like so much water, up the axis of each minute pore of the membrane.

If we have water on one side of the membrane and a saturated solution on the other, we shall find that a certain weight of water passes into the saline solution for every gramme of salt that passes into this water, and the ratio between these has been called the **Endosmotic Equivalent.** This endosmotic equivalent is increased (that is, more water passes into the saline solution) when the pores of the membrane are narrowed, as by chromic acid or by tannin.

Through cow's pericardium, between common salt and water, the endosmotic equivalent is 4; with cow's bladder it is 6.

If blood-serum and a strong solution of sulphate of magnesia be separated by an animal membrane, some sulphate goes into the blood-serum, and some water will enter the saline solution, taking some albumen with it.

When a dead amœba, or a red-blood corpuscle, is put in fresh water the structure swells up and becomes globular.

Curare and snake-poison will not readily pass through the gastric or intestinal membrane: they are, on the other hand, readily absorbed by the dermis or by serous membranes.

Diffusion through the skin, the tissues, etc., is illustrated by the diffusion of solutions of **carbolic acid** in aseptic surgery. These solutions diffuse more rapidly than septic germs can travel; and thus the septic germs, if any, can be caught up by the antiseptic solution and killed.

In the circulation of the **blood** there is diffusion through the walls of the capillary blood-vessels between the blood and the surrounding lymph, and again between the lymph and the tissues themselves.

Water travels more readily inwards through frog-skin, more readily outwards through eelskin.

Albumen more readily passes through a membrane soaked with alkalies.

If the **water** into which the crystalloid may pass be constantly or frequently **renewed**, the diffusion of the crystalloid is **accelerated**, and the crystalloid may thus be wholly extracted from the solution. If the **solution** be **agitated**, the process is **retarded**.

If salts be laid upon the **dermis** they are very rapidly absorbed, for the osmosis through the walls of the lymphatic vessels and veins is accelerated by the **flow of blood** in these vessels. For the same reason substances are very rapidly absorbed by the **pulmonary epithelium.**

If the solution be **pressed** against the membrane the normal process of Osmosis is interfered with, and colloids, such as proteids, may pass through as well as crystalloids, along with liquid forced through by the pressure, even though in the absence of such pressure they may be indiffusible.

Heat favours rapidity of Osmosis; and an **electric current** tends to push the liquid bodily through the membrane, so that even gelatine and the fatty matters of milk can thus be driven through.

The **separation** of Crystalloids from Colloids by means of a **membrane** is called **Dialysis.** When we have to separate a crystalloid poison from the contents of a stomach, for example, we make a dish with a false bottom of animal membrane or of parchment paper, and we stop up any leaks in this by means of albumen coagulated by heat; we float this on water and put the stomach-contents into it. The crystalloid poison passes into the water, while the colloid mucus, etc., remain in the floating dish or "**dialyser.**"

If we dialyse a solution of peroxide of iron in perchloride of iron, we obtain colloid hydrated peroxide of iron left behind in solution. Neutral Prussian blue (as used in microscopic work) may be purified in the same way; so may sucrate of copper, a soluble colloid compound of copper oxide with grape sugar, which is reduced by heating. Albumen may also be purified by dialysing the contained salts out of it.

Osmosis through porous membranes is a somewhat irregular phenomenon, which depends on the relation between the pores and the solid parts of the membrane, upon the width of the pores, upon the nature (colloidal or otherwise) of the walls of the pores, upon the attraction between these and the respective liquids, upon the mutual action of the liquids, upon the relative masses of the molecules, upon the temperature, upon the electrical conditions, and upon the relative pressures on both sides of the septum; and in physiological cases it seems to depend on the influence of the nervous system, which affects the condition of the walls of the blood-vessels. There is, therefore, no simple physical law governing its relations, as there is in the case of true Osmosis through membranes or films devoid of perceptible pores.

When the **pores** are **large**, as in paper or paper pulp or sand, the liquid passes through bodily if exposed to Pressure. This pressure may be due to the Weight of the liquid itself, as in ordinary **filtration**; or to the partial removal of the atmospheric pressure on the side of the filter opposite to the liquid, in which case the atmospheric pressure drives the liquid through; or to a direct squeeze, as in squeezing mercury through chamois leather; or to exposing the liquid to an increased gaseous pressure. In all cases there is a tendency for the substance dissolved to be retained within the pores of the filter: whence sea-water, filtered through sand or canvas, is less saline than at first.

When a **gas** is dissolved in a Liquid, and a layer of the same liquid free from gas is laid upon the solution, the molecules of the Gas diffuse, so that the solution rapidly becomes **uniform**. If two such layers be separated by a membrane which is wetted by both, the diffusion is rapid, particularly if there be relative flow past the membrane.

There is thus a free exchange of Gases, as well as of diffusible Solids, between the blood and the lymph, and between the lymph and the tissues.

Two streams of a liquid, running opposite ways past a membrane, may completely exchange their gases and dissolved salts, if the length of path be sufficiently great.

Evaporation.—In most cases, when a liquid is set aside in the air it dries up: the liquid disappears; its **molecules escape** one by one into the surrounding air, and are carried off by air-currents. This is the process of **evaporation.**

The air or gas in contact with the liquid thus comes to contain more or less of the **vapour** of the liquid evaporated; as for example in the charging of **air** with the vapour of **chloroform** or **ether**, evaporated from a handkerchief or sponge, for anæsthetic purposes; or the saturation of **coal-gas** with **benzol-vapour** to increase its lighting power, or with **alcohol-vapour** to prevent the deposition of ice in the pipes in cold weather.

Spheroidal state.—When a liquid is dropped upon a heated surface, the rapid evaporation of the liquid may cause a **layer of vapour** to lie between the drop and the heated surface, which are, accordingly, **not in contact.** This is seen when water is dropped on a heated flat-iron in order to find whether the flat-iron is hot enough; and it is even possible to put the moist hand into melted metal without burning the hand, on account of the development of this protective layer of water-vapour.

If the liquid evaporated be a **mixture** of different liquids, the general result is that the **most volatile** component of the mixture escapes in greater proportion than the less volatile components.

Chemical affinities, however, sometimes interfere with this: thus if **sulphuric acid** be set aside to evaporate, it will not do so, but increases in bulk; it picks up **water-molecules** from the air, and becomes more dilute. If a mixture of water and alcohol be exposed in a confined space within which there is unslaked quicklime, some water-molecules escape from the liquid along with a greater proportion of alcohol-molecules: the water-molecules are absorbed by the lime when they happen to light upon it: more water-molecules thereupon leave the dilute alcohol, again to find their way to the lime; but the alcohol-molecules attain a condition of **equilibrium**, in which as many molecules return to the liquid as leave it. Strong alcohol may thus be very effectively **dehydrated.**

The preceding example shows us that evaporation of the alcohol comes to an end when the alcohol-molecules, considered by themselves, come to produce a certain **pressure** upon the liquid; and if we were to **raise the pressure** exerted by the alcohol-vapour upon the liquid, the temperature being kept the same, the Condensation would become more rapid than the Evaporation, and then alcohol would be **deposited** in the **liquid** form. Again, at **higher temperatures** Evaporation is **more rapid**, for the Molecules then have greater Velocities and more readily escape. This we may see in the more rapid drying of ink on paper in dry or hot weather. In damp weather, on the other hand, there are already a great number of water-molecules in the air, and the ink may take a long time to dry; for the number of these water-molecules which stick to the ink, when they strike it, is nearly as great as the number which leave the ink for the surrounding air.

On the same principle, when we wish an object—a muscle preparation, a microscopic slide—not to dry up, we may put it in a "**moist chamber**," that is, under a bell-glass in the company of a quantity of well-wetted blotting-paper. The air in the bell-glass becomes charged with water-vapour, and the preparation remains moist, for it picks up as many water-particles as it loses.

For **each temperature** the balance between Evaporation and Condensation is reached at a **different vapour-pressure.** For example, if the temperature be 10° C., this balance exists, in the case of **water**, when the pressure (so far as this is due to molecules of water) is about 0·012 atmosphere, or about 0·916 cm. of mercury. If there be so much moisture in the atmosphere that, of the whole atmospheric pressure, 0·916 cm. of mercury-column is due to the water-vapour alone, wet objects will not dry at all at 10° C.; there will not be any apparent evaporation. The air will then be **saturated** with water-vapour. If there were more moisture than this at that temperature, the atmosphere would be **supersatur-**

ated with moisture, and moisture would condense: if there were less, the atmosphere would be **unsaturated**, and Evaporation would take place from wet surfaces.

Again, if water-vapour be in the air in such quantity as to produce a pressure of exactly 0·916 cm.; then if the Temperature be **10° C.** the air will be exactly saturated, and there will be neither liquefaction nor evaporation: if it rise **above** 10° C. the air will become unsaturated with moisture, and there will be Evaporation: if it fall **below** 10° C. there will be Condensation of moisture from the air, which is then supersaturated.

Let the temperature be say 20° C., and the pressure of the water-vapour 0·916 cm. of mercury, and let a glass of iced water be brought into the room: as soon as the temperature of the air round the glass is reduced to 10° C. there will be condensation of moisture on the glass and on the surface of the iced water; and at 0° C. there will be all the more deposition of moisture.

The **temperature** of 10° C., and the **aqueous-vapour-pressure** of 0·916 cm. of mercury, are thus related to one another; and so are a series of pairs of such terms, which are to be found in "**hygrometrical tables.**"

In the case above mentioned the condensation of moisture begins at 10° C.; 10° C. is the **moisture-condensation-temperature**, or the "**Dewpoint.**" When the air is damp the dewpoint is high; when the air is dry the dewpoint is low, and there must be considerable cooling before there will be any condensation of moisture.

When air containing water-vapour is cooled down to its Dewpoint there is a deposit of **dew.** If this dew is first formed on floating particles of **dust** or smoke, the minute droplets formed may float for a long time, forming a **haze** or a **fog**, any one droplet within which may take a long time to reach the ground, bearing its dust-nucleus with it.

Moisture is deposited from the air, in the form of water, about a **water-bed**, when the water in the water-bed is cold and the dewpoint is high; and from the breath upon a cool **mirror**, such as a **laryngoscopic** mirror. In the latter the proportion of moisture present in the breath is so great that the mirror must be made distinctly warm in order to prevent the deposition of moisture upon it. Similarly, **microscopes** ought to be fairly warm, else moisture is deposited on the lens from the vapour transpired by the skin of the observer.

At ordinary temperatures the air is usually far from being saturated, and evaporation from wet surfaces readily takes place. But if ordinary air be **heated** without our adding moisture to it, still less does it then contain enough moisture to saturate it at its newly-acquired temperature; and **evaporation** from the moist surfaces of the **lungs** is then **too rapid** for comfort. On the other hand, if the air be **nearly saturated** with moisture evaporation from the skin is checked, and we feel the atmosphere **muggy** and oppressive.

The amount of water-vapour in the air may be directly determined by subjecting a known volume of the air to the direct **moisture-absorbing** action of chloride of calcium or of concentrated sulphuric acid, and observing either the **decrease of volume** or the **defect of pressure** induced, or the **increase** in the **weight** of the absorbent.

It is, however, generally sufficient, and more convenient, to find the **temperature** at which **condensation** of moisture takes place. If we know this we can refer to **hygrometrical tables**, and ascertain the corresponding quantity of moisture in the air; and by comparing this quantity with that which would be necessary to saturate the air at its actual temperature, we find the **degree of humidity**.

For example, if the air begin to deposit moisture at 10° C., we know by the tables that the aqueous vapour in the air exerts a pressure of 0·916 cm. mercury. If the air be actually at 20° C., we find that at 20° C. the pressure of water-vapour necessary in order to saturate the air would have been 1·740 cm.; but there is only 0·916; therefore the Humidity is $\frac{0.916}{1.740}$, or 52·64 per cent.

The Dewpoint may be **measured** directly by means of a silver bulb containing ether ($C_4H_{10}O$) in which a thermometer stands. Air is blown through the ether, which is thus made to **evaporate** very rapidly; the bulb is thus rapidly **cooled**: when it reaches the dewpoint its surface becomes **dimmed** by the deposition of moisture. The temperature is noted, and is the Dewpoint required.

For exact readings we have to take the mean between a series of alternate readings of the temperature at which the dimming appears on blowing through, and that at which it disappears when the apparatus is left to itself.

The ether may also be made to **evaporate** in another way, viz., by **cooling** a second bulb connected by a tube with the first. The ether-vapour in the second bulb is thus **condensed**: its place is taken by fresh ether-vapour from the first bulb; this in its turn is again condensed, and so on. The ether in the first bulb is thus kept evaporating, and that bulb becomes cold.

In a Leslie's "**wet and dry bulb**" (sometimes called an August's **psychrometer**), it is not the Dewpoint which is observed, but a phenomenon which depends on the degree of Humidity of the atmosphere.

In this instrument we have two Thermometers: one (the "**dry bulb**") an ordinary thermometer; the other (the "**wet bulb**") a similar thermometer with its mercury surrounded by a well-wetted wick. The readings of the dry and the wet bulb are different: the wet bulb is cooler the greater the evaporation from its wet coating; that is, the less the humidity of the air: but it never actually falls to the Dewpoint itself. Tables have been constructed which, from the readings of the dry and wet bulbs, show the amount of Humidity of the air; and in the use of the instrument these have to be consulted.

For rough observations of the state of the atmosphere, **gelatine films**, which straighten out when damp and curl up when dry: **hairs**, which absorb moisture and lengthen; and even **paper**, which does the same thing, may be used. The hygroscopical properties of **paper** render it unsuitable for accurate **scales** or thermometer-graduation; for its length may vary as much as 1 per cent, according to the dampness or dryness of the weather.

Boiling.—The Condensation-Temperature corresponding to a water-vapour Pressure of 1 **atmosphere**, or 76 cm. of mercury, is 100° C. When water is brought to 100° C., at standard atmospheric pressures it evaporates so rapidly that the escaping **molecules** can bombard and drive away the surrounding **atmosphere, lifting** it up against its **weight.** When this takes place, molecules escape into any cavity formed within the liquid and **bubbles** are formed, while rapid evaporation also takes place at the inner surface of the bubble. These bubbles rise up in the liquid, and the liquid "**boils.**" **Boiling** takes place whenever the outward pressure from the liquid is equal to the atmospheric or other gaseous pressure upon the liquid; and hence at a **height**, where the atmospheric pressure is less, the "**boiling-point,**" that is, the temperature at which boiling occurs, is **lower**; for it is not then necessary for the water to be so hot in order to get up an adequate pressure of steam. Thus at Quito, at a height of 9540 feet, water boils at 90°·1 C.; and if the pressure be reduced say to 0·916 cm. of mercury, as by an air-pump, water will boil at 10° C.

In the **Cryophorus**, liquid in the bulb A (ether or chloride of ethyl) may be made to boil by cooling the bulb B. Apart from the vapour of the liquid, the cavity of the cryophorus is a vacuum; and when B is cooled by ice, the vapour is so far condensed that the liquid in A rapidly evaporates, and may even boil at very moderate temperatures. A secondary effect is, however, that the liquid in A very rapidly **cools** down unless it be kept at the same temperature.

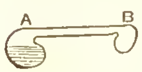


Fig. 104.

In many cases **evaporation** or boiling or distillation is best carried on in a partial **vacuum** continuously kept up; as in the evaporation of sugar-solution in vacuum pans, and in many pharmaceutical operations. The temperature to which the material is exposed is then lowered, and the risk of charring is averted.

On the other hand, if water be heated in a boiler with a **loaded safety-valve**, so that the pressure may come up say to 5 atmospheres before the steam can escape, the water does not boil freely until a temperature of 152·2° C. is attained.

In **sterilising water** at 120° C. for half an hour, the pressure attained in the boiler will be 149·13 cm. of mercury, or 1·962 atmospheres; and our boiler must be strong enough to stand the excess pressure above the external atmospheric; that is, an uncompensated internal pressure of 0·962 atmosphere.

In a **Papin's digester** materials are heated in a boiler with a loaded safety-valve, so that steam does not emerge until the internal pressure is considerable. Under such conditions water acts powerfully as a solvent, *e.g.* on bones, on glass, etc.

When the liquid to be boiled is a **solution** the molecules of the liquid do not escape so readily, and the needful temperature is higher: hence the **boiling-point** of a **solution** is **higher** than that of the solvent liquid alone, and rises with the concentration of the solution.

At the same temperatures, solutions have vapour-pressures which differ from the vapour-pressure of the pure solvent at the same temperature by amounts directly **proportional** to the **number of molecules** of the salt present in the solution, but **independent** of the **nature** of the salt or substance dissolved.

The boiling-point of a saturated solution of calcium chloride is 179°·5 C., and that of one of caustic soda is 215° C.

Statics of Liquids

When a Liquid entirely **fills the cavity** in which it is enclosed its behaviour while at rest is, as regards **pressure**, the same as that of a **gas** which also fills the containing space. Thus we have the Pressure always **at right angles** to the surface; the pressure the **same in all directions** at any given point (Hydrostatic Pressure); and the **Transmissibility of Pressure** to all parts of the liquid, so that the Pressure per unit of Area becomes the same all over the bounding surface and throughout the liquid.

In a **water-bed** or **water-cushion** the water yields, and the bag dilates at the points not pressed upon, until the pressure per unit of area (the "Intensity of Pressure") is the same at all points of the bag. The patient's skin is then exposed to a pressure which is uniform all over, instead of being concentrated on particular regions of support. The **brain** itself is padded on a water-cushion of this kind: for the cerebro-spinal fluid in the subarachnoid spaces supports it in this way.

If an indiarubber bag filled with liquid be inserted in any of the cavities of the human body, and if pressure be applied to the liquid, the bag will **dilate** until the back-pressure **at every point** is equal, per unit of area, to the pressure per unit of area at the point where the pressure is applied. The back-pressure is produced by the **resistance** of the tissues and of the bag itself to **expansion**: and therefore a distensible bag will dilate more than one with comparatively rigid walls. The same principle applies when the **bladder** is being filled with a solution say of boracic acid, poured in through a catheter tube by means of a flexible tube and a funnel placed at a sufficient height.

It is important to note that the mechanical properties of Liquids are shared by the greater part of the **soft masses** of the human body. Even the **brain**, within very small limits of distortion, can act as a practically incompressible liquid, and can transmit pressure from the arterial system to the skull. This may be seen in the pulsations of the **fontanelles** in a young child; or by exposing a given area of the brain by **trephining**, and applying an appropriate pressure-indicating apparatus. If squeezed upon at one place, as by a **blood-clot**, the brain will equalise the pressure by driving blood out through the veins, and will thus become comparatively bloodless, and therefore inefficient: and variations in the blood-pressure within the brain cause corresponding outflows and inflows in the large venous blood-sinuses at the base of the brain.

Even what was said about Gases, at Figs. 84 and 85, that part of the Work expended upon a gas which transmits pressure is expended in **heating** the gas, is true of Liquids; but the compressibility of liquids is so small that we may neglect this altogether; and then we arrive at the proposition that when a Liquid transmits Pressure, the **work** done **by** the liquid against a Resistance is equal to the **work** done **upon** the liquid by the compressing Force. In the **Hydraulic Press** the greater movement of a smaller piston induces a smaller movement of a larger piston, as in Fig. 86; but the Work done by the one upon the liquid is equal to that done by the other against the resistance overcome; and the **force resisted** at C is to the **force applied** at A as the **area** of C is to the **area** of A. Thus if the area of C be 100 times as great as that of A, the **aggregate force** which can be exerted at C is 100 times as great as that applied at A. But it must be noted that **per unit of area** the Pressure at C is **the same** as that applied at A.

In an arterial **aneurysm** there is a small aperture of communication between the inner lining of the artery and a false cavity, into which the blood has escaped and worked its way. This cavity has, upon each **unit of area** of its surface, a pressure equal to that exerted by the blood at the small aperture, again per unit of area. But the bounding surface of the cavity is much larger than the area of the small aperture; and hence the **total pressure** tending to produce dilatation of the cavity is much greater than the pressure upon the small aperture of communication. Over any little area of the bounding surface, equal in size to the aperture of communication, the pressure tending to produce dilatation at that area cannot exceed but will be **equal** to the pressure at that aperture.

When the pressure within a bag containing liquid is great, the bag itself is under stretch and tends to rip open, so that it may in some cases be readily **ruptured** by a comparatively slight accidental blow or additional squeeze.

If the action of a hydraulic press be reversed, we find that the **total force** exerted on the **larger** piston results only in the transmission of a **smaller total force** to the **smaller** piston.

In the same way a large total force exerted over the whole surface of a contractile hollow viscus, such as the bladder, the uterus, the stomach, will result only in the transmission of a moderate total force to the limited area corresponding to the outlet of that viscus.

Heavy Liquids.—In actual Liquids one feature forces itself into prominence, which, though not absent, is of far less importance in Gases—that is, the effect of the **Weight** of the liquid itself.

If there be a Free Surface the atmospheric or other exterior Pressure will affect the free surface; if there be no free surface, that is to say, if the liquid entirely fill the vessel which contains it, the hydrostatic pressure at the **topmost** point of the liquid may be taken as representing the pressure on the **surface** of the liquid. At levels below the free surface or the topmost point, the Pressure within the liquid, though at any given point it remains "**hydrostatic**," that is, equal in all directions, is **greater** and greater **as we descend.** The **additional pressure** at any point, due to the **weight** of the liquid, depends for its amount upon three things: it is equal in dynes per sq. cm. to the *product* of (1) the vertical **depth,** into (2) the **density** of the liquid, into (3) the local **acceleration** of **gravity.**

Thus at a depth of 10 cm. in heavy mineral oil (density = 0·870) it is $10 \times 0{\cdot}870 \times 981 = 8534{\cdot}7$ dynes per sq. cm. Over an area of say 8 sq. cm. this will be $8 \times 8534{\cdot}7 = 68277{\cdot}6$ dynes.

It does not matter in what direction the area pressed upon may be sloped, so long as the Depth is measured down to the **centre of figure** of that area.

Thus the pressure on the iron tubes, boiler, and fittings at the basement floor in the **hot water piping** of a lofty building may be very great, being about one additional atmosphere pressure for every 33 feet of height. When **wood** is dragged **under water,** the water may be driven into its pores, so that the wood becomes heavier than water and rises no more to the surface. In **dropsy** and **varicose veins,** keeping the feet up diminishes the pressure on the veins, by diminishing the actual height of the liquid blood-column. The pressure on the **sides of tanks** is greater the greater their depth, whence it is often preferable to make them broad and shallow.

The pressure on the air within a **diving-bell** is about an additional atmosphere per 33 feet of water; and thus those engaged in pier and bridge building have, while at work, to breathe compressed air.

When a man stands on his feet the blood in his head is exposed to the ordinary Atmospheric Pressure: when he stands on his head the blood in his head is exposed to the atmospheric pressure *plus* a pressure corresponding to the column of blood in the inverted body. Hence in the latter case there is a tendency to congestion.

If a man were to float in a liquid of his own specific gravity, head down, the pressure within the blood-vessels of the head would be actually greater in the same way, but it would be counterbalanced by an **equal increase** in the exterior pressure at a depth within the liquid: so that there would be no congestion.

These two cases may be illustrated by taking a loop of very distensible rubber tubing and filling it with water; suspended in air it is distended below, suspended in water it is relieved of distension.

In the case of a **slack bag** filled with fluid, lying on a base of support, the actual pressure per unit of area depends on the three terms given above; and the Total Pressure on the base of support depends on the area of that basis, together with the pressure per unit of area. If the **abdomen** be considered as a bag filled with practically fluid contents, the pressure on the pelvic basis of support remains the same whether the individual be obese or not; if he be, the contents not overlying the pelvic floor have to be supported by the abdominal walls, as in Fig. 105 *c*.

The Pressure per unit Area is the same for all points of the liquid at the **same horizontal level**; and the outward pressure on the walls, at each level, is the same **all round** the liquid. This outward pressure is always at **right angles** to the walls of the vessel.

In no case does the intensity of pressure at a depth within a liquid depend in any way upon the actual Quantity of liquid which lies above the area in question. For example, in Fig. 105 the **pressure on the base** of the vessels is the **same** in all three cases, the base being equal in all these; and if the bottom be a false bottom of thin indiarubber, this will **bulge equally** outwards in *a*, *b*, and *c*. If *b* were reduced to the form shown in Fig. 106, a trifling additional quantity of liquid in the capillary column B would give rise to an increase in the total Pressure on the base A **far exceeding the Weight** of

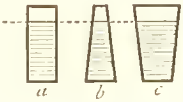


Fig. 105.

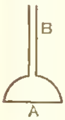


Fig. 106.

the quantity of liquid added. This is what is known by the name of the **Hydrostatic Paradox**; but Fig. 106 is merely another form of the Hydraulic Press, analogous to Fig. 86.

The **strength** of any apparatus of the nature of a flask or **boiler** may be tested by filling it with water and bringing to bear upon the water, through a manometer U-tube, the weight of a sufficiently tall column of mercury. It does not matter in the least whether the column of mercury be a thin or a thick one.

The principle of Loss of apparent Weight on the part of a body immersed in a fluid—**Archimedes' Principle**—applies to Liquids exactly as it does to Gases. This principle is applied to the determination of the Density of a solid body, as we have already seen.

The vertical upward pressure within a liquid **buoys up** any floating body, such as a man swimming, and the Weight of any object immersed seems much reduced. Hence it is easy to **lift** large blocks of stone while these are **under water**, but much more difficult to lift them out of the water; and hence also a **stream** in heavy flood can readily **transport** large masses of **rock**.

If we take two similar glass phials, two small rubber bands and four nails, we may construct a couple of rough models to represent a man with his arms above his head, and a man with his arms close to his sides. On putting these into water the one will float, while the other may very well be submerged. The tendency in both is to sink just so far that the weight of the whole is equal to the weight of the water displaced; but a man with his arms above his head may get his mouth and nose under water before this position of equilibrium is reached.

If we have two **communicating vessels** containing the same liquid, the free surface of which is exposed to the same Pressure, as in Fig. 107, the liquid will stand at the **same level** in the two vessels. If there be any **difference** in the **density** of the liquids in the two vessels (say that the liquids are the same liquid at different temperatures, or that they are different in their

Fig. 107.

nature) the liquid in the two vessels will not stand at the same level. The **pressure** in the communication-pipe must be **equal from both sides**; and as this is proportional, in each column, to the product of the Height of the liquid into the Density, it follows that if the density of either liquid fall short the height must be increased, and *vice versâ*.

By observing such differences of height in two columns of the same liquid, of which one is **heated**, we may ascertain what the Change of Volume is which occurs when a liquid is heated through an observed number of degrees Centigrade, and therefore we may find the **Coefficient of Expansion by Heat** per degree C. The accuracy of the level is interfered with by **capillarity** or surface-tension, in the way already explained, so that corrections have to be introduced in order to allow for this.

Measurement of Liquid Pressure is effected by several instruments, of which many are forms specially adapted for physiological work. We shall mention some of these separately.

1. **Manometric tubes** open at the top. The pressure within A at the level *a* is ascertained from the height and the density of the liquid column *ab*, which is upheld by the pressure at the level *a*. The liquid in the tube *ab* is continuous with that contained in A. If, for example, this liquid be blood (density = 1·055), and if the height of the column of blood sustained in *ab* be 165 cm., the pressure at the level *a* is the product of the height *ab* × density of the liquid × the local acceleration of gravity = 165 × 1·055 × 981 = 170768 dynes per sq. cm. We must add the external **atmospheric pressure**, whatever that may happen to be, to the figure above in order to ascertain the full value of the pressure within A: but if the atmospheric pressure also act upon the contents of A, we do not make this addition.

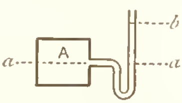


Fig. 108.

2. **Piezometer-tubes**: the same principle is applied; but the tubes **do not bend** below *a*, so that the height *ab* has to be measured from the level of the **orifice** *a*, that is to say, from the **midpoint** of the orifice. Piezometer-tubes are usually applied, when it is possible so to apply them, to the **upper** surface of the liquid whose pressure is to be measured, as in Fig. 109.

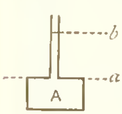


Fig. 109.

3. **Mercury manometers.**—It is seldom desirable to allow any of the **liquid** itself to **escape** from A into manometer or piezometer-tubes, and **mercury** is used as a means of measuring the pressure. The height of mercury-column measures the pressure. Suppose the difference between the levels at *a* and *b* is 12·8 cm. of mercury, then the pressure is 12·8 cm. (height) × 15·596 (density of mercury) × 981 (gravity) = 170768 dynes per sq. cm.

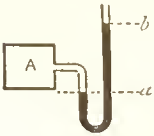


Fig. 110.

4. Even in the preceding form some of the liquid escapes into the manometer tube. This difficulty may be got over by inserting into an aperture in the walls of A a tube with an **indiarubber cap** O. This cap should not be too small in proportion to the size of the tube: or conversely, the bore of the tube should be small; that is to say, the tube should be **capillary.** The mercury should stand at the **same level** in both limbs of the tube before being inserted; if it do not, the datum to be observed is the rise of mercury in the limb *ab* under the pressure of the air compressed by the cap O. This cap O is itself squeezed by the pressure of the liquid into which it is inserted.

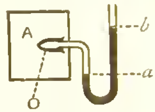


Fig. 111

5. In **Fick's Federmanometer** the manometer is replaced by a contrivance like a Bourdon's **steam-gauge** (p. 101) filled with alcohol. The tube connecting this with the liquid whose pressure is to be found, may or may not bear a cap of indiarubber or similar material, as in No. 4 just mentioned. If the indiarubber cap be absent, the instrument is used, in physiological work, with the tubes filled with a solution of bicarbonate of soda of sp. gr. 1·083, this being the liquid which may be most safely allowed to escape into the blood without producing coagulation of it. The steam-gauge tube or C-tube is made, as it alters its form, to work a lever which bears a **writing-point**; this registers the distortions of the C-tube, and therefore indicates the amount of the pressure to be ascertained.

6. **Sphygmoscope.**—The liquid is continuous from the vessel A to the interior of an **indiarubber cap** B. Movements of the cap cause **varying pressures** in the space C. These pressures are communicated by the tube D to any contrivance which may indicate or be made to record the varying air-pressures in C and D. If the cap B be appreciably distended by the pressure, it exerts an elastic **back-pressure,** and **fails** to communicate to C and D the *whole* pressure exerted upon it. The instrument is therefore only adapted for **small** variations of pressure.

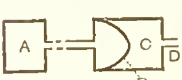


Fig. 112.

7. **Manomètre métallique inscripteur.**—This is, in principle, precisely like the Sphygmoscope, but the place of the indiarubber cap B is taken by a **metallic capsule** B. This is surrounded by liquid, which is squeezed more or less through the tube D.

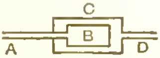


Fig. 113.

8. **Tambours.**—In these the sphygmoscope-cap is made one face of a little drum; and as it **bulges** out and in, it operates the short arm of a light **lever**, whose long arm bears a **writing-point**.

9. **Dr. Roy's apparatus.**—In this the liquid pressure operates an exceedingly light **piston** in a short side-cylinder. The pressure tends to drive the piston along the cylinder; but this tendency is resisted by a light steel **torsion-spring**, whose twist indicates the actual movement of the piston, and measures the pressure which causes this movement.

10. **Maximum and minimum manometers.**—These are manometers provided with **cup and ball valves**, so as to allow liquid to flow freely in one direction, but not to return. The greatest height of column occurring during an experiment (maximum manometer), or the greatest diminution of height of liquid placed in the tube (minimum manometer), can then be ascertained at the close of the observation.

11. **Differential manometers.**—In these, two tambours are used, connected with different points, the pressures at which have to be **compared.** Each tambour acts upon one pan of a **balance**; when the pressures are equal the balance is even; when not, it inclines to one side or the other.

Manometer and piezometer tubes are **faulty** when applied to the measurement of **Variable Pressure**, in respect that the liquid within them tends not faithfully to follow the variations of pressure, but to **oscillate.** The mercury or other liquid, on being set in motion in the tube, acquires Momentum: as the pressure varies, the mercury goes too far, and then falls back too far; and its movements are, besides, affected by **friction** within the tube. If the tube be very narrow (as a whole, or locally only) these oscillations fade away; but the instrument is then **slow in its response** to rapid variations of pressure, and indicates only the **mean pressures.** In Fick's instrument, No. 5 above, the writing levers have connected with them a small disc immersed in **glycerine**; the movements of the levers make the disc move in the glycerine, and the **viscosity** of the glycerine tends to prevent any oscillations. The sphygmoscope, No. 6, and the metallic inscriptor, No. 7, and specially Dr. Roy's apparatus, No. 9, have **little inertia** to combat, and hence their tendency to oscillation is small.

All these forms of pressure-indicator or pressure-recorder—

except Nos. 1, 2, and 3—must, however, be **graduated beforehand** by finding what readings they give under known Pressures; and they must be **tested** from time to time, to ascertain how far they maintain the original absolute values of their readings.

Flow of Liquids

The Flow of Liquids presents many features of importance to the student of medicine, on account of its bearing on the **circulation of the blood.**

We may see a Flow of Liquid when we lift one end of a tank containing water: the water "**seeks its level,**" and tends to keep its free surface always at right angles to the direction in which gravity acts, that is, always horizontal. The whole mass of the water, in that case, brings its **centre of gravity** as **low down** as possible; and any given particle of the liquid becomes **pressed** upon **equally** on all sides, which it would not be if the surface of the liquid were not level.

If an upper overflowing **reservoir** of water be connected with a lower place of outflow by a straight open **channel**, the water will flow down the channel in a continuous **stream.** The water in contact with the **walls** of the channel does **not flow** at all: the water most nearly in contact with the walls moves least: and the **quickest** part of the stream is the **central** superficial portion A. Assume that the slope of the channel is gentle, so that there is no turbulence in the water; then the water may be assumed to glide along smoothly in such a way that all successive portions reaching the same point follow the same course, which is parallel to the walls of the channel so long as the walls of the channel are straight and parallel. The Direction of Flow at any point of the stream is a **line of flow** or **stream line** at that point. Fig. 115 illustrates the lines of flow in a uniform

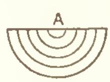


Fig. 114.


Fig. 115.

steady stream. But if the channel widen out or narrow down, the lines of flow become farther apart or nearer together, as in Fig. 116. In all such cases it is to be observed that where there is **widening** the flow must **slow down**, and where there is narrowing the flow must become more rapid: but the actual **amount of liquid** flowing in the stream must be **the same** in all parts of the stream, be these narrowed or widened. Leonardo da Vinci, who was a great hydraulic engineer as well as a great painter, formulated the law that the **velocity** of the current at any point was **inversely proportional** to its **cross-sectional area** there. All this assumes, as has been explained, that there is no turbulence or broken water in the stream.

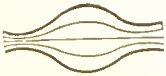


Fig. 116.

A stream of liquid has, of course, **momentum**: it has also a certain amount of **cohesion**: it is thus readily enabled to leap over a chink when its volume or its velocity are considerable. This principle has sometimes been utilised, as in cases where liquid sewage is allowed to fall through chinks in sloping gutters, whereas when a shower of rain comes on, the greater volume of water, running with greater speed, leaps over these chinks, and thus does not dilute the sewage itself, but is directed elsewhere.

In the **water-supply** of a city or town, a **reservoir** is filled with water and placed in communication with the **water-mains**. The water tends to reach the lowest possible position, and it **flows** along the pipes. At the reservoir itself the water at the inlet to the mains is subject to a Pressure corresponding to the Weight of a superjacent column of liquid, extending upwards from the level of the inlet to the level of the surface of the water. And more than that, as the pipes come down the hill-side from the reservoir, the pressure in the mains tends to increase, for the vertical height of the water in the reservoir above any given point of the main is greater and greater. But at the outlets there is no resisting pressure; hence there is a considerable **difference of pressure** between the water **in the mains** and the water at the **stop-cocks**; and the consequence of this is a **flow** of water through a tap when the stopcock is opened.

Since liquids tend to flow downwards, necessarily all **drainage-tubes** should lead downwards; and **incisions** for surgical drainage purposes, as in dropsy or abscess, should be at the **lowest** suitable point.

When two liquids of different specific gravity are brought into communication, the **heavier** one **uppermost**, the heavier liquid tends to **flow down** through the lighter one, and thus to lower the Centre of Gravity of the whole as much as possible. For example, when mercury is poured into water it sinks to the bottom. If a bottle of water be inverted in a quantity of spirit, the water flows out and spirit takes its place.

Instead of our producing a difference of pressure by means of a difference of water-level, we may do so by the direct application of Force or **pressure** to the water at one part of a system of pipes. Thus we have water made to flow with great velocity by means of the **fire-engine**, in which the water is firmly pressed upon in the cylinder, and allowed free exit at the nozzle of the hose.

Without multiplying examples, it may be said broadly that **flow** of Liquid is **caused** or determined by a **Difference of Pressures** between the different parts of a mass of liquid.

But it would not do to make this statement without qualification. It is **not every difference** of Pressure which will cause Flow. There is a difference of pressure in every case in which liquid stands in a vessel or tank: the upper layers are subject to the atmospheric pressure only, while the lower are subject to the atmospheric pressure *plus* the weight of the superjacent layers; and yet there is not flow, but Equilibrium and Rest. To induce Flow in a liquid contained in a tank it will suffice to open an orifice in the bottom or side of the vessel; then the liquid flows out and escapes; but by doing this we have set up a new difference of pressure, a difference of pressure which did not previously exist, when the mass was in equilibrium. Before opening the orifice there was equilibrium between the Pressure of the liquid on the walls of the vessel and the Reaction of the walls of the vessel on the liquid; but after opening the orifice, the **pressure** of the liquid outwards through the orifice is not **counterbalanced** by any such **reaction**, and the liquid at the orifice flows away, while its place is continuously taken by fresh portions of liquid, which are successively exposed to similar conditions; the result is a continuous **stream**. The Difference of Pressure which produces Flow is therefore something **superposed** upon those differences of pressure which naturally arise in a liquid exposed, as all masses of Liquid must be, to the influence of Gravity.

Should the pressure outside the tank be greater than that inside it, then on opening the orifice liquid may be forced into the tank, instead of issuing from it.

In the case of a tank of water with an orifice opened at its bottom or side, there is no doubt that the actual pressure at or near the orifice internally is not equal to the **hydrostatic pressure** (= Height × Density × 981, per sq. cm.) which may be measured there when the orifice is closed: it is smaller; but the whole question is very much simplified by the circumstance that the **outflow** is the same, when once a **steady stream** has been set up, *as if* we had to deal with a full and undiminished Hydrostatic Pressure internally.

There are two ways of stating the amount of pressure under which the liquid is being driven through an orifice. Firstly, we may say that the Pressure per unit of Area is equal to so many **units of force** or Dynes: or, secondly, we may say what **height** of the liquid in question lies above the orifice in question, and by its Weight forces liquid out through that orifice. The usual way of giving the last-mentioned particular is to state that the **Head** of the liquid is so many cm. or inches: and the liquid is said to issue from the orifice under a certain specified "head," H.

If p be the Pressure (in units of force per unit of area, dynes per sq. cm.) and H the equivalent Head of liquid (in cms.), $p = H\rho g$ dynes per sq. cm., where ρ is the density of the liquid and g the local acceleration of gravity. The Pressure on the orifice is, accordingly, greater in a heavy liquid than in a lighter one under an equal Head.

According to what is known as **Torricelli's Law**, a **jet** of liquid issues from an orifice with a **velocity** exactly **the same** as that which any given portion of the liquid would have acquired if it had **fallen** freely downwards from the level of the surface of the liquid to the level of the orifice. The actual speed is such that this law is very nearly obeyed: there is hardly one per cent of error in the result.

This speed is v (cm. per sec.) $= \sqrt{2 \times 981 \times H} = 44 \cdot 3\sqrt{H}$, where H is measured in cms. It will be observed, on looking at this formula, that nothing is said in it about ρ, the density of the liquid; the fact is that the velocity v, for a given head H, does not depend on the density ρ; the velocity of the outflowing stream will be the same whether we fill our given tank to a given height with water or with mercury. Though the driving pressure is greater in a heavier fluid, the inertia of the mass to be set in motion is increased in precisely the same ratio: and thus nothing is gained in speed by endeavouring to utilise the greater weight of the heavier liquid, so long as the liquid to be driven is the same as that whose weight drives the stream. If, however, we try to drive a lighter liquid in a stream by means of the fall of a heavier one, we may give the lighter liquid an extreme velocity: for example, we may fill a two-corked flask with water and fit a fine nozzle into one cork and a funnel into the other: then on pouring mercury into the funnel, the water will rush with great velocity through the nozzle. What potential energy the mercury has lost in falling the water has gained: and as the mass of the water per unit of volume is smaller, its velocity must be greater than that of the mercury. The water rises to a height greater than that from which the mercury had fallen. The Velocity of Outflow does depend, however, inversely on the square root of the density of the liquid exposed to a given actual driving pressure: under a given Pressure a liquid four times as heavy will flow only one-half as fast. It also depends on the square root of the driving pressure, so that a liquid under a four-fold pressure will flow twice as fast.

All this applies, so far, to jets of liquid; and in jets of liquid we have certain peculiarities to remark.

Jets of liquid mostly assume a parabolic form as they pass through the air, because any given portion of the liquid begins to fall as soon as it is free to do so: the onward movement possessed by it as it left the orifice, compounded with the accelerated downward movement due to its free fall under gravity, results in each such portion travelling in a parabolic path: and we see a series of such portions simultaneously; so that the flow takes the form of a continuous parabolic jet.

Again, the form of a jet is such that it is usually **narrower** at a little distance from the orifice than it is where it emerges from the vessel. But this narrowing may be greatly modified by the various forms of nozzles, or **ajutages**, which may be fixed to the orifice. A short cylindrical tube may make this narrowing disappear.

Then when a jet has emerged into the air, as it falls it comes to fall more and more rapidly, and therefore tends to **thin away**; for the stream is accelerated and, as it were, stretched in its lower part. And it is hardly possible to prevent it from **vibrating**: but if it do so at all, any portion of the stream which is in vibration tends to oscillate in portions alternately thinner and thicker: and then, as the stream thins away, the oscillation overpowers the tenacity of the stream, and the stream breaks up into **drops**. These drops go on oscillating and changing their form as they fall. The phenomenon is one of **free fall in air**, and it does not explain the vibration of liquids in tubes, though this explanation has been suggested. It depends largely on the **surface-tension** of the liquid.

A jet sometimes seems to have a **screw form**. This will occur when the jet issues from a **linear orifice**. The jet is then flattened to begin with: but it tends, in virtue of its surface-tension, to become cylindrical. It therefore contracts as it travels: but the adjustment to a cylindrical form overshoots the mark, and the jet becomes flattened in a plane at right angles to the former. The consequence of this is that it again contracts, and again overshoots the mark: so that alternate portions of the jet are flattened in different senses, and any given portion of it **oscillates** through a number of different cross-sectional forms, while the jet as a whole seems, but is not, screw-shaped.

If, nextly, we have to do not with an orifice in the side of a tank, but with a **pipe**—for simplicity's sake, a horizontal pipe—leading from the tank, we find that the **pressure** within that pipe is **not the same at all points**. If it be a **uniform** pipe, smooth and rigid, we find that a series of little vertical branch-pipes, **piezometer-tubes**, will have water standing in them even though liquid flows along the main pipe EF; and this water stands at heights which **diminish regularly** from

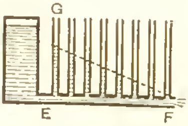


Fig. 117.

the tank to the outlet, so that the upper ends of the columns can all be joined by a straight line, as in Fig. 117. All along such a pipe the **velocity of flow** is constant; and the **slope of the line** GF is also constant.

Take any one piezometer-tube: water stands in that tube at a certain height; it does not fall away into the main stream; up to a certain limit it is easier for water to climb up the piezometer-tube than it is for it to flow on with the stream—up to a certain limit, but not beyond: and when that limit has been reached, it is easier for the water to flow along with the stream than it would be for it to push or thrust more water up the piezometer-tube, against the downward pressure or Weight of the water which already stands in that tube. The **Height** of the water in any given piezometer-tube serves as a means of measuring the local **pressure** within the pipe; and if we look at the Pressure within the stream at any point as being "**back-pressure**" at that point, we see that it is the same thing as the local **Resistance** which the stream offers, at that point, to its own progress.

The Resistance offered to onward Flow, and the consequent back-pressure, may be traced to several causes. Among these, one is the **viscosity** of the liquid. When a liquid flows, it always undergoes a Shear: each layer slips over the layer next to it. In a tube each such layer is tubular. The outmost tubular layer **remains in contact** with the wall of the pipe, and does not pass on, that is, if the wall of the pipe is **wetted** by the liquid. The next slips upon this, and the next again upon that, and so on; so that the axial part of the stream moves the most rapidly: and in this axial part we see the red-blood corpuscles travelling in capillary blood-vessels. This slipping of one layer upon another brings **Friction** into play; and to overcome this requires the application of **driving pressure** continuously applied. The **Work** spent in overcoming this Friction appears as **Heat** in the liquid, which becomes more or less warmed.

Under a given pressure, the Quantity of Liquid which will pass through a pipe in a given time depends upon the amount of this internal Friction: the less this is, the less will be the Resistance to flow: and in a very narrow tube the law expressing the relation between this internal friction and the corresponding amount of flow is a comparatively simple one: but in a wider pipe the amount of flow is interfered with by another circumstance, which is that in a wider pipe there are always **swirls** and **eddies** formed. These swirls and eddies obstruct the onward flow, and induce waste of Energy in the production of Heat; and they are specially well marked wherever the pipe suddenly widens or bends or divides into branches. They are also produced whenever the walls of the pipe are rough. Mere roughness of the walls of the pipe would not tend to displace a steady stream once set up; but it tends to prevent the setting up of a steady stream, through deflecting the stream lines into one another and causing **eddies**, particularly when the driving pressure is itself variable or intermittent. Again, where the liquid **does not wet** the walls of the pipe, Work must be done in forcing the liquid along, past these walls; so that in this case we have **surface friction**; and in order to overcome this, Pressure must be continuously exerted.

Let us now look at any given length, say 300 cm., in such a pipe, and by means of piezometer-tubes find what the heights of the columns of liquid supported are, at the beginning and very near the end of the 300 cm. in question. Let us say that these are respectively 25 cm. and 15 cm. of water. We know that a column of 25 cm. of water corresponds to a pressure of 24525 dynes per sq. cm., and one of 15 inches to a pressure of 14715 dynes per sq. cm. The Difference of Pressure per sq. cm. is 9810 dynes along the whole 300 cm., or a difference of 32·9 dynes per sq. cm. along each single linear centimetre of the pipe. This Difference of Pressure per linear cm. or, generally, per Unit of Length, is directly represented by the **slope** of the line GF (Fig. 117).

In calculations we would have to use this Fall of Pressure, or of remaining Resistance, per unit of length. This is otherwise known as the **Pressure-Slope**. Then the velocity v of flow of the stream would be, according to the formula in use, such that the Pressure-Slope, in proper units, is equal to $\rho g(av^2/r + b/v^2)$, where ρ is the density of the liquid, g the acceleration of gravity (=981), r the radius of cross-section of the pipe, and a and b are constants which must be ascertained by experiment. We do not propose, however, to take in hand any algebraical calculations of this kind; and it will be sufficient in the meantime to examine the figure itself (Fig. 117) a little more closely, and to come to some conclusions as to its possible variations.

As an experimental fact, the **pressure** in the **first**

piezometer-tube of all, just outside the tank, is **not so great** as the pressure **within the tank** would have been, at the same level, if there had been no flow. The liquid in the first piezometer-tube, therefore, stands at a lower level than the liquid in the tank itself. This is partly due to **eddies** at and about the inlet of the pipe EF: but the fall of pressure due to this may, for most purposes, be neglected. The main cause, which we shall treat as the only cause, of this fall of level is that the liquid does acquire a certain Velocity, and issues at F as if a **certain amount** of the **original head** of water were **used up** in giving it that **velocity.** It is as if F were an **aperture** in a vessel from which liquid was issuing in a **jet** with the observed velocity v: then by Torricelli's Law, the Head of liquid which must be maintained in that vessel, in order to maintain that velocity of flow, is $H = v^2/1962$. This amount of Head has to be subtracted from the original or driving Head of liquid in the tank; and it is only the **remainder** which can possibly be effective in producing **pressure** within the pipe EF.

If we completely drop from view all Eddies and all their consequences, we reach the statement that the **pressure** in the pipe as near as possible to the tank corresponds to a certain portion of the original or driving Head; that the actual **velocity** of flow corresponds to another portion; and that these two portions completely account for, and that their sum is equal to, the original Head of water in the tank. The portion of the original head which corresponds to the actual Velocity of flow may be called the **Velocity-Head**; the portion which is expended in overcoming the Resistance to outflow from the tank, or in setting up the various Pressures within the pipe, may be called the **Pressure-Head**, or the **Resistance-Head**; and these are together equal to the original total **Driving-Head.**

Obviously, so long as we keep the Driving-Head the same, if we diminish the Resistance-Head we increase the Velocity-Head; and *vice versâ*. If we increase the Velocity-Head, we of course increase the Velocity of outflow: if we increase the Resistance-Head, we increase the Resistance and the Pressures within the outflow-pipe. Again, if we increase the Resistance offered by the pipe to onflow through it, we increase the Resistance-Head at the expense of the Velocity-Head, and therefore at the expense of the Velocity of outflow: and this increase in the Resistance offered by the pipe may be effected by narrowing it, or by lengthening it.

We have therefore to consider (1) the **Driving-Head**, which corresponds to so much driving Pressure or Force applied to the liquid in the pipe; (2) the **Velocity-Head**, which corresponds to the actual Velocity of the liquid in the pipe (this velocity being proportional to the *square root* of the velocity-head); (3) the **Pressure-** or **Resistance-Head**, which is measured by the height of liquid column sustained in the first piezometer-tube; (4) the lateral **Pressures** at the piezometer-tubes, which pressures sink uniformly from a pressure corresponding to the full value of (3) in the first tube, down to a zero value at the orifice of outflow; and (5) the **Resistances** to onflow, which depend on the conformation of the pipe itself and which are measured, at any point, by the value of the lateral Pressure at that point.

These things depend on one another. Let us, without altering anything else, **increase** (1), the **Driving-Head**; then both (2) and (3) are increased, and accordingly both the Velocity of onflow and the lateral Pressures are increased; and the line of pressure-slope, GF (Fig. 117), becomes **steeper**.

The increase of (2) is proportionately a little greater than the increase of (3); so that (2) gets a little more than its proportionate share of the increase in (1).

It will be kept in mind that the Velocity-Head is proportional to the *square* of the Velocity; so that if we quadruple the driving pressure we do a little more than double the velocity of flow in a pipe, while we at the same time do a little less than quadruple the pressures.

If the Driving-Head be **diminished** the velocity and the pressures fall off; and the velocity-head falls somewhat more rapidly than the pressure-head.

Next, with everything else as at first, let us **increase** (5), the **Resistances**, by narrowing or lengthening the pipe: this obstructs the onflow, diminishes the velocity and the velocity-head, and correspondingly increases the Pressure-Head and the lateral Pressures. If, on the other hand, we widen or shorten the pipe, we increase the onflow, and thus increase the Velocity and the Velocity-Head, and diminish the pressure-head and the pressures.

Next let us both **increase** the **driving pressure** and, at the same time, **increase** the peripheral **resistance** by narrowing or lengthening the pipe; we are sure to **raise the pressures** in the piezometer-tubes; and we *may* increase the Velocity or, by increasing the resistances sufficiently, or by keeping down our increase of driving pressure, we may on the whole diminish it; but it will be possible to **adjust** the peripheral Resistance to the actual increase of driving pressure (or else to restrict the increase of driving pressure in accordance with the actual increase of peripheral resistance) in such a way that the **velocity of onflow** may remain **as before.**

Thus when the placental is added to the ordinary circulation, the flow of blood in the blood-vessels is less easy; the heart must produce greater pressures, and therefore must work harder, in order to keep up the same stream; and it tends to become hypertrophied.

If we **reduce** the **driving pressure** and at the same time **shorten or widen** the outflow-pipe, we are sure to **reduce** the piezometer-**pressures**; we may, by sufficiently shortening or widening the pipe, or by limiting our reduction of driving pressure, increase the Velocity, or by not doing so we may decrease it: or, by due

adjustment of the peripheral Resistance to the actual decrease of driving pressure (or else by restricting the diminution of driving pressure in accordance with the actual decrease of peripheral resistance) we may leave the **velocity** of onflow **as at first.**

Next let us **increase** the **driving pressure,** and at the same time **diminish** the peripheral **resistance** by widening or shortening the outflow-pipe. We are sure to **increase** the **velocity** of flow: and by sufficient widening, or by keeping down the increase of driving pressure, we may diminish the Pressures: with insufficient widening or excessive increase of driving pressure, the pressures are on the other hand greater than at first; but by suitably **adjusting** the widening or shortening to the actual increase of driving pressure (or else by restricting the increase of driving pressure so as to suit the actual widening or shortening) we may cause the **pressures** to remain **as at first.**

If we **diminish** the **driving pressure** and at the same time **increase** the peripheral **resistance,** we certainly **diminish** the **velocity** of flow: and we may increase the Pressures by sufficient narrowing of the pipe, or by limiting the decrease in driving pressure, or may diminish them by insufficient narrowing, or by allowing the driving pressure to become too small; but we may again **adjust** the narrowing, or restrict the diminution in the driving pressure, so as to leave the **pressures as at first.** Hence, if we increase the peripheral Resistance and thus diminish the onflow, but wish to keep the Pressures the same, we must diminish the driving pressure; but we thereby still farther reduce the flow.

The **heart** has an automatic regulating mechanism of this kind: when the blood-pressure in the blood-vessels is too high, the nervous system makes the heart beat less frequently.

Observation of the Pressures or of the Velocity alone is therefore insufficient to give us full knowledge of the variations in mechanism of this nature, as regards the driving pump or the condition of the pipes themselves.

Unchanged pressures with **diminished velocity** denote diminished driving pressure and a pressure-compensating increase of peripheral Resistance; unchanged pressures with **increased** velocity indicate increased Driving Pressure with a pressure-compensating decrease of resistance.

Unchanged velocity with **diminished pressures** denotes diminution of driving pressure with a velocity-compensating diminution of resistance: with **increased** pressures it denotes increase of Driving Pressure with a velocity-compensating increase of Resistance.

Increased pressures with **increased velocity** indicate increase of Driving Pressure, not fully compensated as regards pressure by a sufficient fall, or as regards velocity by a sufficient rise, in the resistance. With **decreased** velocity increased pressures indicate a rise in the Resistance, not fully compensated as regards pressure by a sufficient fall, or as regards velocity by a sufficient rise, in the driving power.

Decreased pressures with **increased velocity** denote diminished Resistance, not fully compensated as regards pressure by a sufficient rise, or as regards velocity by a sufficient fall, in driving pressure. With **decreased** velocity decreased pressures indicate decrease of Driving Pressure, not fully compensated as regards pressure by a sufficient rise, or as regards velocity by a sufficient fall, in the resistance.

If the pipe be **not uniform**, but increase in its diameter, being **conical** in its form, the **velocity** of the stream **falls off**, and the **pressure** either **increases** or else falls off less rapidly than it would do in a uniform pipe. When the flow is from a narrow into a wide pipe without any gradation of diameter, the **pressure** is **greater** in the **wider** pipe than it had been in the narrower one. The reason of this is that whereas we might have expected the wider pipe to offer a facility rather than an obstruction to the onward flow of the liquid, the reverse is the case: the rapidly moving liquid in the narrower pipe is hurled against the comparatively stationary liquid in the wider pipe, and is brought to a comparatively-slow velocity, with formation of **swirls** and **eddies**. But the pressure so reached must always be less than that near the tank, else the liquid would not flow along the narrower pipe at all. If the pipe expand gradually, in a conical form, and not abruptly, the condition is more favourable to the maintenance of a steady flow ; the stream-lines may simply diverge without formation of eddies ; and in that case the pressure may fall off steadily but more slowly than before, or may even remain constant throughout the length of the expanding tube.

If the Driving Pressure be not uniform but Variable, the pressures in the pipe and the velocities in the stream follow the variations of the driving pressure.

The variations of pressure in the pipe are, however, somewhat smaller, and those of the velocity of the stream are somewhat larger than the variations of the driving pressure would themselves lead us to expect.

If the Driving Pressure applied to a liquid within a rigid pipe be itself **intermittent**, the tendency is to move a quantity of liquid *en masse* at each impulse, like a poker struck endwise by a hammer. An incompressible fluid would move in this way within a rigid tube : any actual liquid is slightly compressible, and its movement is not quite so abrupt : but if the pipe be **rigid**, or practically rigid, this tendency is always well marked, as is the case in **atheromatous arteries**, which are distinguished from normally extensible arteries by the abrupt onflow of blood within them.

If liquid, flowing steadily along a rigid pipe, have its onward flow abruptly checked, as by the sharp closing of a stopcock, the onflow may continue in virtue of the onward **momentum** of the flowing liquid : and the pipe may by this means be exposed to a very severe internal pressure before the onward motion of the liquid is arrested. This may cause severe jolts of the water-pipes within a building. The principle has been utilised in the **Hydraulic Ram**, in which a stream of water is alternately set up and suddenly cut off. At each cut-off the pressure becomes very high ; the water is thus enabled to force a valve, which it otherwise could not displace : it enters a small chamber containing a limited volume of air ; and the air, becoming compressed, in its turn drives the water out at a high mean pressure through an exit pipe.

When the pipe though rigid is not straight, but contains a **bend**, this bend offers an obstruction to the flow. The liquid is driven up against it and forms **eddies**; and thus Energy is wasted. After this obstruction has been passed, the liquid is at a **lower pressure** than it had been immediately before reaching the bend; but the slope of the line GF is equable in all such portions of the pipe as are straight and uninterrupted, and uniform in diameter; for the actual velocity of flow is the same throughout each such portion.

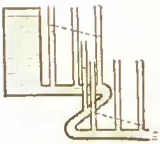


Fig. 118.

If in such a case the driving pressure be intermittent, the **bend** is, as it were, **hammered** by the abrupt impact of the liquid; and if the bend be to some extent distensible, it is **driven forward** by the blow. This condition is exemplified by the **locomotive pulse** in atheromatous arteries: the radial artery seems to plunge forward at each pulsation.

Where we have to do not with an unbranched but with a **branched pipe**, there is a new element to be considered, namely, the total amount of **surface-area** of the walls. A proportionate increase of surface-area determines an increase in the **resistance** offered to the onward flow. It will not do to say that the liquid has to rub against this increased surface; the liquid rubs only against an immovable layer of liquid which adheres to the walls of the channel: but in every case, the greater the surface-area in proportion to the cross-section of the channel, the more play is given to the **viscosity** of the liquid, and the more hampered is the onward flow. On the other hand, a branched system may present on the whole a greater cross-sectional area to the onflowing liquid: the tendency of this is to diminish the total Resistance offered by the path which the liquid has to traverse, and thus to diminish the Pressure near the tank, and to increase the Velocity of outflow from the tank. At the same time, if the total cross-sectional area is being increased, there will be a **slowing-down** of the stream at the branching, and therefore a tendency to increase the Pressures; and conversely, if the branches come together again, so as to converge upon a narrower area, the Velocity will be increased and there will be a tendency to diminish the pressures. Accordingly, if a pipe branch out into a system of numerous pipes which, taken together, present a wide channel for the stream, and if these pipes unite to form again a single channel of the same dimensions as the first, the **pressure** at the **midpoint** of the system is **greater** than the **average** pressure throughout the whole system.

This is exemplified in the circulatory system of vertebrates, in which the pressure in the capillaries is greater than half the mean pressure in the aorta.

If we have two such systems, one larger in scale than the other, but about the same in the relative proportions of the parts, measured linearly, so that the one may be reasonably regarded as a model of the other, the Resistance offered by the one system to the flow of liquid may be approximately the same as that offered by the other, if the Velocities be the same in both. Thus an elephant and a mouse may have approximately the same blood-pressure in the aorta. The mouse has the smaller vascular surface-area for the blood to be forced past: it has the smaller distance to drive the blood from the heart to the extremities; but the elephant has the compensating advantage of the larger blood-vessels and a wider vascular system.

Suppose a tube to **branch** into two tubes of **unequal dimensions**: the **resistances** offered by these tubes will in general be **unequal**: the pressures within the entrance to each will be unequal; and the flow through the tubes will be unequal. The **greater flow** will be along the tube which offers the **less resistance.**

Suppose again that in a branched system, in which a flow has been set up, **some** of the **branches** become **narrowed** or obstructed. The narrowing of any part of the total system diminishes the carrying power of the whole, and the **total onflow** is on the whole **diminished.** The **pressures throughout** the whole system are **increased,** in the unnarrowed as well as in the narrowed branches. So far as regards each of the unnarrowed branches, the slope of the line GF becomes steeper in it; and the **velocity** of the flow through each **unnarrowed** branch is therefore **increased,** just as if the Driving Pressure itself had been increased. This state of things is of importance in reference to the pathology of **congestion** in the circulatory system.

In all flow of liquid through **sufficiently wide** tubes there are **swirls** and **eddies,** and the stream-lines are not truly parallel to one another even in a uniform tube: and the flow is therefore not truly steady. It is only perfectly **steady** in sufficiently **narrow** tubes. For water a tube of less than $\frac{1}{50}$ inch diameter will be sufficiently narrow to allow steady flow: for treacle a tube an inch in diameter would do the same thing. This steadiness in very narrow or "capillary" tubes, and the want of steadiness of flow in pipes of ordinary size, result in this, that the amount of outflow in the two cases is regulated by very different laws.

In capillary tubes it is proportioned not to the square but to the fourth power of the diameter of the tube; it is directly proportional to the driving pressure, not to its square root; it is inversely proportional to the length of the capillary tube; and it is inversely proportional to what is known as the Coefficient of Viscosity. That is to say, the more viscous a fluid is, the less of it can you drive through a capillary tube under a given pressure in a given time; and the comparative viscosities of two liquids under the same conditions, or of the same liquid under different conditions, may be compared by seeing what quantities can thus be forced through a capillary tube in a given time. The capillary tube employed must be of adequate length, otherwise the conditions come to resemble those presented by a wide tube.

The viscosity of a liquid is usually less when it is warm; and Dr. Graham Brown has found that the blood, at fever temperatures, is less viscous than it is at normal temperatures; and that to such an extent that the strain upon the heart in keeping up the circulation is actually lessened by reason of the diminution of viscosity induced by an abnormally high temperature.

Even when a stream has been set up in a capillary tube, it is to be observed that if the speed of onflow be sufficiently increased, the stream may break up into eddies; and thus one and the same tube may act as a wide tube for rapid streams, and as a narrow or capillary tube for slow streams.

In any case where the **pressure** at any point in a stream has to be ascertained, it will **not** do to **stop or obstruct the stream** in any way. The stream must be allowed to flow on uninterrupted and unobstructed: and the apparatus employed must be so contrived. The piezometer-tubes employed must, therefore, not encroach in the least on the lumen of the tube.

Where it is necessary to measure the **velocity** of a stream various methods may be adopted, of which the following are the principal:—

1. **Optical.**—Determination of the speed of small **particles floating** in the liquid; *e.g.*, red-blood corpuscles in the capillaries. This is only an approximate method. If the particles be of the same density as the liquid they will roll into the axial stream, and the larger they are the more are they retarded by the peripheral parts of the stream; if not, they will float or sink and **roll** upon the walls of the vessel, and their speed will be affected by **rolling friction**, which depends on their relative **lightness or heaviness** and also on the **stickiness** of these particles or of the walls of the vessel or tube. Alterations in the density of the blood may cause red-blood corpuscles to float or sink, and therefore to roll; and the blood-vessels may become abnormally sticky, so that the corpuscles tend to block up the bends.

2. **Chemical.**—The time is found which elapses between the introduction of a dissolved substance into the stream, and the arrival, at a determined point, of liquid in which that substance can be detected by chemical means, or else by the alteration of the liquid in respect of its electrical conductivity.

3. **Volumetric.**—(*a*) Cutting the vessel and measuring the outflow; *but* this disturbs the pressures and increases the velocity, while if the stream be a closed circuit loss of liquid deranges the whole working.

(*b*) Interposing a tube of known cubical capacity, containing liquid, in the course of the stream, and finding how long it takes to replace the liquid in the tube by liquid from the stream. This is not easy to find, and the interposition of the additional Resistance disturbs the velocity of flow.

(*c*) Making the tube of method (*b*) a vessel of large capacity and small resistance, and so arranging the apparatus that when the vessel is on the point of being completely emptied the course of liquid in it can be suddenly reversed. This is repeated several times, and the time necessary to pass a given bulk of liquid through the circulation is ascertained (Ludwig and Dogiel's **Stromuhr**).

4. **Mechanical Methods.**—(*a*) A very small pendulum swung in the stream is deflected by it in accordance with the Velocity. This is applied in the engineers' **hydrostatic pendulum** and, for physiological purposes, in the **hæmotachymeter**; and in the **hæmodromometer** the pendulum itself consists of the lower end of a needle thrust through the walls of a blood-vessel.

(*b*) **Pitot's Tubes.**—Two tubes (Fig. 119) inserted into the stream; one with its lower end facing the stream, the other turned away from it. The columns of water in A and B are at different heights: and the difference of height depends upon the velocity.

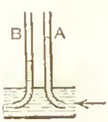


Fig. 119.

(*c*) **Wheelwork**, like **gas-meters.**—A fan or turbine is worked by the stream, and an indicating train of wheelwork works a dial-pointer.

(*d*) **Venturi's Water-meters.**—The piezometer-pressure at a wide part of the tube is less than that at a narrow part, to an extent which depends on the velocity.

All these mechanical instruments must be graduated by exposing them to streams of various known velocities, and marking the corresponding positions at which the recording index stands.

The **work** which is expended in driving a **given quantity** of liquid in a jet or stream is equal (in ergs) to the *product* of the **Weight** of that liquid (in dynes) into the **Driving-Head** (in cms.); or, otherwise expressed, the product of the **Driving Pressure** (in dynes per sq. cm.) into the **Volume** (in cub. cm.) of that liquid. In either case, jet or stream, the Driving-Head is the **total head**, that within the tank.

For example, let the question be to ascertain what Work the **human heart** does. The data are: mean pressure in the left ventricle = 12·8 cm. mercury-column = a driving pressure of 170,722 dynes per sq. cm. = a driving head of 165 cm. of blood; liquid propelled at each systole 170·6 cub. cm. or 180 grammes, the Weight of which is $180 \times 981 = 177,580$ dynes. Then the Work done at each systole is 177580×165, or $170722 \times 170{\cdot}6$, both = 29,128000 ergs. If there are 72 pulsations per minute, the work per minute is $(29,128000 \times 72)$ ergs; nearly 150 foot-pounds per minute, or about $\frac{1}{220}$ horse-power on the average, a degree of activity which would raise the heart's own weight about 22,000 feet in an hour, or raise a 200-lb. man about 45 feet in that time. It will be observed, however, that the heart has not 60 seconds per minute in which to do this work: its contractions only occupy on the whole about 21 seconds out of each minute; so that its mean activity during its actual contractions is as much as $\frac{1}{80}$ horse-power.

Part only of the **work** which is done by the driving pressure in keeping up a stream in a tube is converted into **kinetic energy** in the liquid, the Energy of Flow; the remainder is transformed into **heat**, and the liquid is warmed.

Thus far we have considered the flow of liquids in pipes or tubes which are **rigid** or practically so. In many important cases—*e.g.* the arteries and other vessels through which blood is propelled by the heart—the walls of the vessels are not rigid, but are more or less elastically distensible. We have therefore now to consider the Flow of Liquids in such **elastic tubes.**

In the first place, an elastic tube through which a **constant flow** is maintained comes to act practically like a **rigid tube.** The internal pressure of the stream has a certain effect in dilating the tube; and this effect is greater where the pressure is greater; but a condition of **equilibrium** is soon attained, and is thereafter maintained; and then there is no variation in the dimensions of the tube so long as the steady flow is kept up.

Next, if the flow be deliberately **intermittent**, each inflow **dilates** the tube, and the dilatation **dies away** as the inflow ceases. The tube itself thus has work done upon it at each inflow; and it then restores that work as it regains its primitive form when each inflow ceases. But let us suppose that the successive inflows follow one another up with a certain rapidity. Then before the effect of one inflow has died away another has already begun. The tube is thus never allowed to regain its normal form completely; and the outflow and pressure never sink to nothing. There is therefore always some degree of continuous outflow, though there may be throbbing and spurting as in an artery when cut; and the stream may thus present variations in velocity and pressure, which keep time with the rhythm of the intermittences of the driving pressure applied. The more rigid the tube, or the wider or the shorter it is, the more difficult is it to keep up any degree of continuity of outflow, and therefore the greater must be the frequency of the intermissions; and, on the other hand, the more distensible the tube, or the greater the resistance offered to flow through it, the less frequent need the intermittences be. If, however, we look into the matter a little more closely, we see that it is an inadequate statement of the fact to say merely that the tube dilates under the sudden and brief impulse of a momentary driving pressure. It is, in the first instance, not the whole tube but the part of the tube nearest to the source of driving pressure which dilates: a distant portion of a long tube may remain at first unaffected, and if it be very distant, it may be some time before any disturbance reaches it. The tube is thus locally distended; a pouch is formed: but this pouch tends to regain its primitive form: the elasticity of the walls of the tube comes into play; and the liquid in the pouch is squeezed forward along the elastic tube. The next moment, the liquid which has been forced into the tube is found occupying a longer and slenderer pouch farther along the tube; and the dilatation of the tube thus seems to travel along in the same direction as the flow of liquid, the pouch becoming continuously longer and slenderer as it travels.

Suppose that instead of a sudden increase of pressure we have a **sudden defect of pressure** in the tube, which is still supposed to be filled with the liquid; the tube partly **collapses** in the neighbourhood of the source of defect of driving pressure, and liquid is withdrawn from it; but the tube tends to regain its primitive form, and the **collapsed form** is **passed on** from portion to portion of the tube. The collapsed form is better marked at first than it is when it has travelled for some distance; as in the previous case, that of dilatation, the change of diameter becomes smaller, but at the same time longer and longer portions of the tube are affected, as the disturbance travels along the walls of the tube. The flow of liquid, to make up for what has been withdrawn from one end of the tube, is in this case in a direction opposed to that in which the distortion of the walls of the tube travels.

If the finger-tip or the extremity of a lever be laid on such a tube, the arrival of the dilatation or expansion can be felt or observed: and the dilatation or expansion (followed by a more gradual waning away of the distortion) travels like a wave, which wave is called a **Pulse-Wave.** The speed of travelling of this wave varies according to circumstances; it is greater the greater the **thickness** of the wall: it is greater the greater the **resistance** offered by the substance of the wall to **stretching**; it is **less** the greater the **diameter** of the tube: and it is **less** the greater the **density** of the liquid within the tube.

The **length** of a single **pouch** or pulse-wave in such a tube is the product of the **speed of propagation** of this kind of disturbance into the **time** during which the inflow is being kept up: for example, the tendency is for each pulse-wave in the blood-vessels of a man to have a length equal to the product of the velocity of propagation (10 to 18 metres per second) into the time of systole of the heart ($\frac{1}{3}$ second), or from $3\frac{1}{3}$ to 6 metres. Of course there cannot be complete pulse-waves of such lengths as these in the human body; and what happens is that the blood-vessels never do relax and assume a completely normal form, for the next pulse-wave is upon them before they have done so. The **arteries** are thus **always** in a state of **tension**, though this is variable.

In the case of **indiarubber**, the elasticity, or resistance to stretching, remains much the same whether the deformation of the tube be great or small: and hence larger and smaller pouches are propagated at about the same speed; but in the case of **arteries** the conditions are different. In an artery, the more it is stretched the more it resists stretching; a wide dilatation is therefore propagated more rapidly than a narrow one; a full pulse travels more rapidly than one of small expansion.

To arrest the passage of a pulse-wave a certain Pressure is required. When this pressure is applied by means of an instrument of the nature of a spring balance, we have the **Sphygmometer**, used in measuring the pressure necessary to extinguish the radial pulse.

In a branched system with numerous branches the small branches wear down the pulsations, and the pulse-wave disappears. Thus in the arterial blood-vessels we have pulsations; in the capillaries and veins normally none, except in such cases as that of the activity of a salivary gland, during which the arterioles are dilated, and there is a "**venous pulse**" continued into the corresponding vein.

A driving pressure **gradually** applied will cause a correspondingly gentle slope at the front of the pulse-wave: a pressure **abruptly** applied will cause an abrupt local expansion of the tube and a steep-fronted pulse-wave. **Rigidity of walls** favours **shallowness** of the wave, for then the rate of propagation is great, and the dilatation at any one point is correspondingly small. **Peripheral resistance** hampers onward flow, and therefore favours wide pouching of the elastic tube and a slow disappearance of the pouch.

Still closer inquiry shows us that we generally cannot confine ourselves to *single* pulse-waves in elastic tubes. When an elastic tube is pouched by the sudden inflow of liquid, the elasticity of the tube brings the tube back to its normal dimensions; and if the outflow be restricted, this process will be a gradual one, so that the tube steadily regains its normal form. But if the outflow be easy, if there be little obstruction to the escape of the vigorously injected liquid, the walls of the tube, in promptly regaining their normal position, generally overshoot the mark. At the same time the liquid itself tends to do the same in virtue of its inertia. On the whole, the portion of the elastic tube previously pouched becomes more or less collapsed for the moment. The tube then regains its form: liquid runs back to fill it; but this may again overshoot the mark. A series of **secondary oscillations** may thus be set up.

The **human pulse** shows phenomena of this order. Sometimes the first of these secondary oscillations is not incomparable with the primary pulse-wave itself. This condition is apt to occur when the walls of the vessels offer much resistance to being stretched. In all cases, however, the second, third, and succeeding secondary oscillations are of very minor importance.

It may perhaps be noted that in the arteries there sometimes is, between the primary wave and the first secondary wave, a sinking and a sudden recovery of pressure which gives the appearance of an interpolated undulation, and makes the pulse "**dicrotic.**" There has been some discussion as to the cause of this: and it has been explained as being due to the sudden cessation of pressure exerted by the ventricle of the heart, followed by the sudden closing of the valves, which suddenly arrest back-flow from the aorta or pulmonary artery into the corresponding ventricle. The conditions for this are that the arteries be highly distensible and elastic, the mean pressure low, and the heart-stroke firm.

In any event the secondary waves are not so high as the primary: and hence while in caoutchouc tubes they travel at about the same speed, in **arteries** the **secondary** waves **travel more slowly** than the primary, so that they lag farther and farther behind them.

The elasticity of a tube may have still further consequences. Suppose that a pouch travels along to the end of a long tube, and that the liquid does not there find a ready outlet, the tube will locally get rid of its deformation by **reflecting** it backwards along the tube, and the front of the reflected pulse-wave may meet and complicate the hinder part of the primary pulse-wave: yet under such conditions the actual small outflow at the distal end of the tube may be curiously uniform. And more, the amount of **outflow** from such a tube may, if the pulsations be frequent enough, be **more abundant** than from a rigid tube of the same normal width, and bearing an equal terminal aperture, when exposed to exactly similar conditions. The **dilated** elastic tube offers on the whole **less resistance** to flow of liquid along it to the terminal aperture than the unwidened rigid tube does: and thus it gains an advantage over the rigid tube. Consequently, if such a distensible tube should become **rigid**, it would be necessary, in order to keep up the same Flow, that the **driving pressure** should become **greater.**

This necessity accounts for the **hypertrophy** of the left ventricle of the heart when the distensible arteries become comparatively rigid through **atheroma**: for the heart has then to work harder in order to keep up the same flow, and its left ventricle, which drives the blood through the arteries, consequently becomes of abnormal size.

Solidification of Liquids

When a liquid becomes cold enough it will solidify or "freeze." Even liquefied air will do this, and become like snow.

In many cases we find that our ordinary temperatures are low enough to enable the solid form or state of a substance to have become the one most familiar to us. For example, we usually see iron as a solid; and we have to go to an iron foundry in order to see it as a liquid. In our temperate climates mercury is a liquid; but in an Arctic midwinter it is a solid, and can be hammered like lead.

When a liquid becomes a solid its molecules largely, if not wholly, lose their power of slipping past one another; and their mean free path must become very restricted.

Solids

A substance in a **perfectly solid** state would possess the following characteristics: (1) a **definite Form** of its own; (2) **Resistance** to **Deformation**; (3) **Permanence of Form** so long as the surrounding conditions remained unchanged. A Solid would **not** continuously **flow** as water or treacle will; it has a form of its own, and does not necessarily come to fit the vessel in which it is placed, as water or treacle do: much less will it occupy it wholly, pressing against all its sides, as a Gas will do.

There are, however, many substances, which we call Solids, which do continuously **flow**, though extremely **slowly**, under the influence of sufficient causes: cobbler's wax, sealing wax, will flow down hill: hot glass, paraffin, wax, selenium, guttapercha, Canada balsam, a mixture of glue and honey, all **soften** and become unable to retain their shape long before they positively melt by heat; even **metals**, exposed to sufficient distorting stresses during protracted periods, may slowly yield and alter their shape. During the moulding of a bullet in a bullet mould, during the stamping of a coin at the mint, the metal is being so distorted that its particles flow past one another; and this flow is kept up until the metal has, under the Pressure exerted, flowed into every crevice of the mould or die. Such solids are said to be imperfectly solid, or quasi-fluid, or **plastic**. Some metals can be drawn into wire by being pulled through small holes in a hard steel plate: here the molecules of the metal pass one another, on their way through the steel plate, in the same fashion as the molecules of water do when issuing in a thin stream through a fine aperture in the bottom of a tank. Such metals are said to be **ductile**. Some metals are extremely ductile, *e.g.* gold, silver, and platinum.

Platinum wires of exceeding tenuity, and only distinctly visible when made redhot in a flame, are made, as for use in the **micrometer eyepiece** of a microscope, by constructing a thick silver bar with a platinum core, drawing this out to an extreme fineness, and removing the silver by immersion in nitric acid.

Again, some Solids can be deformed by the hammer without breaking at the edges: gold can be beaten to gold leaf of extreme tenuity; and such substances are said to be **malleable.** During the impact of the hammer the action is one of Flow, producing an irreversible deformation. Other substances there are, such as antimony, diamond, glass, which fly to pieces at the first blow of the hammer, and are said to be **fragile.** From these instances it will be seen that the distinction between a Solid and a Liquid is a matter of degree; and some substances stand in the borderland between solids and liquids.

Solids differ, again, in their relative **hardness** and **softness.** The criterion of these properties is, that of two substances, that which is said to be the **harder** can **scratch** the other; and in this sense diamond and carborundum are the two hardest substances known.

The determination of hardness is affected somewhat by the form of the bodies: thus a pin can be made to scratch glass, though glass is harder than pin-metal: and if the relative movement be very rapid, very hard substances may be cut into, as in the sand-blast (a stream of sand rapidly blown through a tube), which can cut through rocks and even through steel.

Most Solids are not without some degree of **porosity.** Hydrogen diffuses through baked unglazed clay, and wind can even blow through bricks if unpainted: and earth-gases can travel even through hydraulic cement if not tarred. Mercury can be squeezed through chamois leather: water can be squeezed through gold or lead: and petroleum soaks through iron.

The special properties of Solids seem to be due to the arrangement of their **molecules.** These appear to be more interlocked or **mutually connected** in some way than they are in Liquids or Gases: and in this way they form together a more connected system. Even on bringing two solids together the particles may come within the sphere of one another's forces, and then it may be difficult to pull the two masses apart. Thus we have **cohesion** of two masses of the same solid, as for instance where two perfectly smooth faces of glass or of freshly cut lead or of polished steel cohere with great tenacity when the air is squeezed out by pressure from between them; or where we have the cohesion of two white-hot surfaces of iron or platinum in the process of **welding**. We may also have **adhesion** between two different solids, as for example the adhesion of glass to a dried-up solution of gum-arabic, or the direct adhesion of silver to platinum at 500° C. From the same cause we have the **tenacity** of a steel wire, to which a great force must be applied before it can be broken by pulling it lengthwise; and even such a substance as marine glue is very tenacious.

We often find adhesion of a solid to a moist surface; glass, breathed upon, adheres to chamois leather, as is seen in the cleaning of cover-glasses: and slight **damping** of a surface often greatly increases the **friction** between it and a body slid over it.

Sometimes the Molecules are so aggregated as to form a system which is in **unstable equilibrium.**

If a little mass of fused glass be dropped into cold water the exterior is suddenly chilled: the interior has to accommodate itself to this as it best can: it does so, so as to possess a greater volume than it normally would have at its actual temperature; and when the product, a so-called **Rupert's drop**, has one end broken off, the whole flies to powder. To prevent such strains as this existing within a cooled mass it must be **annealed**, that is, allowed to cool extremely slowly: large optical lenses are sometimes kept gradually cooling for weeks: the particles then adjust their mutual relations in the quasi-fluid or plastic state of the glass, so that when the whole is cooled there is no such strain. **Steel**, again, is apt to present similar phenomena, and unannealed steel may be as brittle as glass: and **iron castings**, which are not usually annealed with special care, are apt to snap and fall to pieces if they be damaged, or if they be quenched with cold water when hot. **Thick glass**, blown in the open air in the usual way, is apt to be more or less in the condition of a Rupert's drop: and the slightest scratch will often shiver a tube of thick glass, or one presenting extreme variations of thickness: and the practical rule is that apparatus of glass presenting this feature should never be rubbed with any metal harder than copper.

So long as a Solid remains unbroken or undeformed, its **molecules seem** to have **no relative movement**, such as that which the particles of a gas present.

This is, however, not absolutely the case. The particles of a solid do, of their own accord, travel a little; powders may act upon one another chemically to a slight extent when mixed, as if they were in solution: and if sulphur and a powdered metal be mixed and pressed together, a certain proportion of the sulphide of the metal may be formed. Again, the surface of a solid is not indifferent to the chemical substances and compounds contiguous to it; hot iron oxide gives off oxygen to hydrogen, and hot iron takes up oxygen from steam; phosphorus absorbs the vapour of carbon disulphide and liquefies; boxwood charcoal absorbs gases and causes them to combine chemically; platinum black absorbs oxygen and hydrogen and causes them to combine, and it also has a powerful effect in promoting the clotting of blood. Such facts seem to show that the movement of the molecules of a Solid, though limited in comparison with that of the molecules of a Gas, is limited merely and not non-existent.

Deformations of Solids

By the application of sufficient Deforming Force it is always possible to distort or deform a Solid more or less.

A **Perfect Solid** is an ideal not realised in practice. If such an ideal perfect solid were exposed to any deforming force or cause of deformation, the **deformation** set up would remain **the same** so long as the cause of deformation was **kept up**.

It is true that wires on which heavy masses are suspended not only stretch at first, when the Weight exposes them to Tension first of all, but also go on stretching extremely slowly when the action is continued; and an analogous effect is observed in many other cases: but these effects are so small that it is more convenient to attribute them, as we have already done, to a certain degree of Fluidity existing even in the most rigid Solid. We therefore consider only the former of these effects, the deformation produced immediately and once for all.

The **deformation** produced by a deforming force is **proportional** to the **Deforming Force** applied: Hooke's Law; "Ut tensio sicut vis." For example, if the weight of 1 kilogr. will stretch a given thick piece of indiarubber $\frac{1}{10}$ cm., the weight of 4 kilogr. will stretch it $\frac{4}{10}$ cm.

Deformations are of four main kinds: **Shrinkage or Dilatation, Lengthening or Shortening, Shear,** and **Twist.**

Shrinkage or Dilatation is scarcely entitled to the name of Deformation in the usual sense of the term. It means a **change of volume**; and it may be brought about either by **compression,** through a **hydrostatic pressure** being applied evenly all over the surface of the solid, or by a **change** in the **temperature** of the solid.

All solids **shrink** when **compressed**; and with very few exceptions, such as indiarubber, solids **expand** when **heated** and shrink when cooled; so that bodies which when cold exactly pass through certain apertures, will not do so when hot.

Pressure.—If a solid be immersed in a liquid contained in a strong steel cylinder, completely filled with the liquid and closed by a screw stopper, which is screwed in so as to put the liquid under hydrostatic Pressure, the solid immersed in the liquid will shrink somewhat. Usually the Change of Volume produced is very small; but the "Compression" is the **ratio** between this **change of volume** and the **original volume.** Let the original volume be 10 cub. cm., and let the volume become 9·999 cubic cm.: the change of volume is 0·001 cub. cm.; and the Compression is the ratio between the change of volume 0·001 and the original volume 10, that is, $\frac{0 \cdot 001}{10}$ or $\frac{1}{10000}$. Then, next, we have to consider the "**Compressibility**"; this is the amount of the Compression **per unit of** hydrostatic **pressure** applied; that is, per sq. cm. of the surface. For example, if a compression of $\frac{1}{10000}$ be produced by the application of a uniform or hydrostatic pressure of 1,000000 dynes per sq. cm., the Compressibility $= \frac{\text{"Compression"}}{\text{Pressure applied per sq. cm.}}$

$=\frac{1}{10000}\div 1000000=\frac{1}{10000,000000}$. Thus the **Compressibility** of a substance has to be distinguished from an actual **Compression** produced in a given mass of that substance.

Heating.—In a precisely analogous manner we give a name to the **ratio** between the **change** of **volume** and the **original volume**, when the change of temperature is 1° **C.**; and we call this the **Coefficient of Cubical Expansion by Heat.**

If a solid increase in volume from 1·0000 to 1·0009 under a rise of temperature of 3° C., the coefficient of cubical expansion by heat is 0·0003. If a block be cut from this material, the volume of which is 10 cub. cm., what will be its volume at 15° C.? The coefficient of cubical expansion is 0·0003; and the **increase of volume** will be 0·0003 cub. cm. per cub. cm. per degree C., or $0{\cdot}0003\times 10\times 15=0{\cdot}045$ cub. cm. in all; so that the volume will rise from 10 cub. cm. to 10·045 cub. cm.

Examples of Expansion by Heating.—The **stopper** of a stoppered **bottle** may be loosened by winding string round the neck and pulling it backwards and forwards so as to develop Heat by Friction: the neck dilates before the stopper is affected.

When a **flask** is heated, it expands **as if** it were **solid** throughout; if it contain liquid, the liquid may first shrink back in the neck of the flask, on account of the dilatation of the flask: and it is only if the dilatation of the liquid, when it does become heated, be greater than that of the flask, that the liquid will rise in the neck of the flask. To this cause we may trace certain small errors of the Thermometer.

Heat applied to **thick glass** makes the surface expand, while the interior is still unaffected; the glass breaks. If the glass be **thin**, as in a thin **flask**, there is no great difference in the expansion of different parts of the glass, and thin flasks can be used for boiling liquids in. Where the Coefficient of Expansion by Heat is **small**, as in the zinc-borate or the baryta-borosilicate glass used in Jena flasks, thicker flasks can be used to the same purpose.

The Coefficient of Cubical Expansion by Heat may be found by finding the **Density** of the substance at different temperatures: then the **volumes** at the respective temperatures are inversely proportional to the densities; and from the alteration of volume, the original volume, and the difference of temperature, the coefficient of cubical expansion may be found.

Lengthening or Shortening is a **change of length** of a bar or rod or wire of a solid; and in any given case the bar or rod or wire is lengthened or shortened by a certain **fraction** of its original length.

In the case of lengthening, this **fraction of the original length** is called the **Elongation** produced.

An elongation may be produced in two ways: (1) by exerting a pull, or **tension**, on the solid; or by a **change** of its **temperature**.

All solids **lengthen** when **stretched**; and with very few exceptions, such as indiarubber, solid bars or wires **lengthen** when **heated**, and shorten when cooled.

Lengthening under Tension.—The stretching Force or **Tension** required to produce a given proportionate Elongation is the same, whether the rod or wire be long or short, so long as its thickness remains the same.

For example, if a rod of say 100 cm. in length lengthen by say 0·01 cm., a rod of 1000 cm., of the same thickness and under the same stretching-force, will lengthen by 0·1 cm.; the fraction, the "elongation," the ratio $\frac{0.01}{100}$ or $\frac{0.1}{1000}$, remains the same.

If, however, we alter the stretching force applied, we find that the Elongation is **proportional** to the Force so applied; and further, that the thinner the wire the greater the elongation produced.

But we have at hand a convenient means of allowing for the thinness or thickness of the wire or rod by specifying not the Total Force applied, but the pull or **traction** upon the wire, in dynes per square centimetre of cross-sectional area of the wire. Then we say that the **Elongation** is directly **proportional** to the **traction**.

If the wire be 100 cm. long and the extension be 0·05 cm.: then the "Elongation" is $\frac{0.05}{100}=\frac{1}{2000}$; and if the Total Force applied so as to produce this elongation be the Weight of 10 kilogrammes or 100000 grammes (so that the total force applied is equal to 9,810000 dynes), and if the thickness of the wire be such that its cross-sectional area is 1 sq. mm. or $\frac{1}{100}$ sq. cm., then the "Traction" is $\frac{9810000}{\frac{1}{100}}=981{,}000000$ dynes per sq. cm.: and accordingly the Elongation $(=\frac{1}{2000})$ is equal to the Traction (981,000000) multiplied by a fraction, which fraction is equal to $\frac{1}{1962{,}000{,}000000}$. This last fraction is called the "**extensibility**" of the substance experimented on; and the "Extensibility" of a solid is measured by the **Elongation** produced by a **unit traction** (one dyne per sq. cm.)

Muscles have greater extensibility when they are in a state of physiological contraction than when they are at rest: and a muscle loaded with a certain weight and then stimulated to contract may actually lengthen for this reason. Muscles also become more extensible shortly after death.

In nearly all cases, when a wire or rod is stretched by force it **thins out**; but there are exceptions to this. Cork, for example, if pulled upon and stretched, retains nearly the same diameter; but this is a property closely related to the altogether exceptionally great degree of Compressibility which cork is found to present.

Lengthening by Heating.—In an analogous manner, we call the **elongation** produced by a rise in Temperature of **one degree** Centigrade, the **Coefficient of Linear Expansion by Heat.**

This coefficient is very nearly equal to one-third the coefficient of cubical expansion; for if a cube dilate from 1·0000 to 1·0003 on being heated through 1° C., any of its edges must lengthen from 1·0000 to very nearly 1·0001.

If a bar of $17\frac{1}{2}$ cm. in length, at a temperature of 0° C., be cut out of a substance whose coefficient of linear expansion is 0·0001, what will be the length of the bar at 15° C.? The increase in length will be $0·0001 \times 17\frac{1}{2}$, or 0·00175 cm. per degree C.; and for the 15° C., it will be $0·00175 \times 15 = 0·02625$ cm. The bar therefore assumes a length of 17·52625 cm.

The coefficient of linear expansion of a solid may be found by direct observation. The amount of lengthening of a bar or rod, heated to a known temperature, may be measured directly with the aid of a traversing bar and micrometer; or it may be made to cause a displacement of a mirror which then reflects light to a different spot on a screen; or the bar, expanding within a heated tube, may be made to push out a piece of porcelain which can move outwards, but cannot return.

In the laying of **railway rails** their summer expansion and winter contraction must be allowed for, by not laying them in contact with one another. Railway **distance signal rods** have to be tightened up when they are warm, for they lengthen.

In the **compensation pendulum** the Centre of Gravity of the pendulum is kept at the same distance from the point of suspension, whatever the temperature. The lengthening of an iron pendulum by heat would tend to lower it; but by means of **brass** bars which expand in a contrary direction and with a

greater coefficient of expansion, the centre of gravity may be maintained at a constant level. Sometimes a vessel of **mercury** is fitted on the pendulum; as this expands, its own centre of gravity ascends: and the quantity of mercury may be so adjusted as, by this ascent, to keep the centre of gravity of the whole pendulum at the same level.

Fig. 120.

When a metal bar cools between two fixed supports, the pull it may exert upon these supports is enormous; for it is the same pull as would be required in order to produce a lengthening equal to the contraction which the cooling tends to cause.

Within narrow limits the amount of shortening of length, or **longitudinal compression**, produced by making a heavy mass rest on the top of a rod, placed vertically, is the same as the amount of lengthening which would be produced by hanging the same heavy mass upon the rod. Also, such shortening is usually accompanied by lateral dilatation, but not in the case of cork.

When a rod is **bent** there is a combination of longitudinal stretching and longitudinal compression. Suppose a rod to be arranged in a horizontal position, with one end firmly fixed. It may be bent by its own Weight; and it will certainly be bent, to a greater or less extent, if we hang a sufficiently heavy mass on the free end. The **upper** side of the rod, which is convex upwards, is being **stretched** and tends to crack; so that if we take a knife and make transverse scratches in it we may weaken it very much. Glass treated in this way may even be shivered by letting sand drop on its upper surface. The **lower** side, which is concave downwards, is under longitudinal **compression**: so that scratching the under aspect in the same way, or even cutting notches in it, may do no harm. Between the compressed and the stretched region there is a **neutral line**, which is bent out of its original form, but is exposed neither to compression nor to extension, and retains its original length.

A glass filament can be appreciably bent while a glass rod cannot. Before we actually put the longitudinally stretched aspect under a breaking stress, the flexure may be considerable in the case of the filament, but the limit is soon reached in that of the rod.

Shear.—When a solid is sheared, its parts **slip** over one another as the leaves of a book may do when the book is squeezed out of shape. In Fig. 121 (*a*) and (*b*) represent the original and a sheared form of a cubical mass of the solid. The line AB has been turned into the direction A′B. The angle between AB and A′B is the **angle of shear**: and a Shear is measured by the ratio between the slip or displacement AA′ and the distance AB: that is, **the shear** is equal to the **tangent** of the **angle** ABA′.

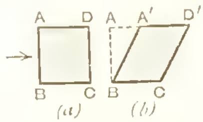


Fig. 121.

If we apply twice as great a deforming force, we double the shear; that is, we do not double the angle ABA′, but we double the slip AA′, and therewith we double the *tangent* of the angle. Therefore the Tangent of the angle of shear is proportional to the Force applied: and if we find the value of the **tangent** of this **angle of shear** when the **shearing force** applied is **unity**, we reach the value of the "**Shearability**" of the substance in question.

How should Shearing Force be **applied**, and how is it to be **measured**? There is more than one mode of stating this.

One way is to consider the lower plane BC as held fast, and a uniform pressure of so many dynes per sq. cm. applied to the face AB in a direction parallel to the face BC and to the resultant shearing or slipping motion. If AC be a cubical block of india-rubber, and if the face AB be pushed in the direction indicated by the arrow, while BC is held fast, the rubber will undergo a Shear and will thus assume the distorted form indicated in Fig. 121 (*b*) above. The amount of Shear (the tangent of the angle of shear) will in this case be so much per unit of pressure applied per sq. cm. of the face AB. If now instead of pushing the face AB, the finger be laid on the top of the block and be pushed along in the line AD, parallel to the previous direction, again there will be a Shear; and if the Force so applied be the same per sq. cm. of the face AD, as it had been per sq. cm. of the face AB, the Shear will be the same as before. Or again, instead of considering AD as being pushed along in this way and dragging the substance of the block along with it, we may distribute the pressure and apply half of it to pushing the face AD in one direction and the other half to pulling the face BC backwards; an action which can be illustrated by taking a book in the two hands, and pushing one cover laterally while pulling the other in the opposite direction, so as to cause the book to be sheared out of shape. The total Shear produced by applying pressure to a given block of a shearable solid in any of these ways is the same, provided that the total Pressure applied is the same in all.

The **force** which must be applied in order to produce a **given Angle** of Shear is always **the same** whether the layer be **thick or thin**; but since the travel from A to A′ is greater when the layer is thick, a given small displacement of A in the direction AA′ is more easily effected the greater the thickness AB of the layer to be distorted.

Torsion.—The next kind of deformation we have to consider is Torsion or Twist. Suppose we have a rod of metal, firmly fixed at one end to a solid support: we want to twist that rod. If we tried to twist it by operating upon its central or axial line we would fail; we must contrive to apply Force at some **distance** from that axial line, so as to get leverage or purchase or **torque**. If, then, we grasp the free end by means of a pair of grippers and prise it round, we find that the farther away from the axis we apply the force, the easier it is to produce a twist; so that our power of twisting depends upon the **moment** of the Force applied round the axis of the rod twisted. When the rod has been twisted, the end prised round has been rotated through a certain angle: let us call this angle the **Angle** of **Twist** of the rod. Then the **angle of twist** is found to be **proportional** to the **moment** of the **force** applied; and it comes to the same thing whether we use a smaller force applied at a greater distance or a greater force applied nearer at hand.

The angle of twist also depends upon some other things. It is directly proportional to the **length** of the wire; it is less the greater the **thickness** of the wire, and that in the sense that it is inversely proportional to the *fourth power* of the thickness, so that a wire half the thickness will undergo sixteen times as great an angle of twist, other conditions being equal;

and it is directly proportional to the shearability of the material of which the wire consists.

When we get down to objects as thin as silk fibres, or those delicate quartz fibres which Professor Vernon Boys has made by melting a drop of quartz and drawing that drop asunder by means of firing off an arrow from a bow, their extreme thinness, coupled with the circumstance that the force necessary to produce a given rotation is inversely proportional to the *fourth* power of the thickness, enables forces to be measured which are incredibly small.

If a long slender bar be hung horizontally, suspended at its midpoint on a wire or thread or fibre, and if a gentle force be applied to the end of the suspended bar, the bar will move round until the tendency of the suspending fibre to untwist comes to prevent any further rotation. The fibre is itself twisted during this operation. We observe the Angle of Twist: we know from previous experiments on the same apparatus what angle of twist a given Torque can produce; we know the Distance from the suspending fibre at which the force is applied; and we easily find, from these data, the amount of the Force now applied. For example, if a torque or moment, whose value is 600 dyne-cms., produce an angle of twist equal to 20°, and if an unknown small force, applied at a distance of 12 cm. from the suspending fibre, cause a twist of 2°, we get the rule-of-three statement that 20° : 2° : : 600 dyne-cms. : (12 F) dyne-cms., where F is the value of the Force we wish to measure. From this we find that $F=5$ dynes. As might be expected, the delicacy of apparatus constructed on this principle makes their use difficult; but Torsion, with fine filaments, affords us a most sensitive means of measuring small Forces.

In most apparatus of this kind, it is not well to allow the force to cause rotation of the suspended bar if it can be avoided: for the change of position of the point of application of the force may either cause a local variation in its amount, or may alter the moment of the force by altering the effective leverage (Fig. 29). It is therefore very common to provide that the suspended bar, though subject to the action of the twisting Force, shall retain its original position. This is effected by twisting the upper end of the fibre in an opposite sense by means of a milled head, graduated so as to show the amount of its rotation. When it has been rotated so as to twist the suspended bar back into its original position against the efforts of the twisting Moment applied to it, it is as if the suspended bar had been fixed and the upper end of the fibre twisted: the amount of rotation in the fibre is the same; but it is more accurately measured, for the original cause of error is now eliminated. Again, the total rotation in the fibre may be divided between a rotation of the lower and an opposite rotation of the upper end of the fibre. The whole rotation in the fibre is the arithmetical sum of the two opposite rotations.

When the twisting force has a moment or "torque" equal to 1 dyne-cm. (as, for example, where the force applied is one dyne at a distance of one cm.), the Angle of Twist will be a certain fraction of a Radian. This fraction is called the "**torsibility**" of the wire employed.

When a rod or wire or fibre is twisted with one end fixed, as we go from the rotated to the fixed extremity of it, we find that each successive section of it is rotated through smaller angles, each proportional to the distance from the fixed extremity. Accordingly, if the rod had originally been marked with **longitudinal lines** or ribs, these lines or ribs would, after the twist, be found to have assumed a **slanting** form: and if the twist be such as to carry the free end several times round a circuit of 360°, these lines or ribs would each present the spiral form of a **screw-thread**.

We have thus considered the various elementary deformations which a body may undergo: and we have seen that the Compressibility, the Extensibility, the Shearability of a substance, the Torsibility of a wire, are the respective Deformations undergone under the influence of unit Forces or a unit Torque as the case may be.

The next question is, **What amount of Force** (or of Torque) is requisite in order to produce a given **Deformation**? Let us take **stretching** as an example. We have seen that the Elongation is equal to the Extensibility multiplied by the Traction: and therefore for a given elongation the necessary traction is equal to the required elongation divided by the extensibility, or multiplied by $\frac{1}{\text{Extensibility}}$. This fraction, $\frac{1}{\text{Extensibility}}$, is a constant for each given substance, and is known as the "**Young's Modulus**" of that substance. Hence to stretch any substance so as to impart to it a given proportionate elongation, the necessary Traction is equal to the required Elongation multiplied by the Young's Modulus of that substance.

Thus in steel wire the Extensibility is about $\frac{1}{2,400000,000000}$, and Young's Modulus is therefore about 2,400000,000000. Accordingly, if we want to stretch a 100 cm. wire to a length of 100·1 cm., the required Elongation is $\frac{1}{1000}$, and then the necessary Traction is $\frac{1}{1000} \times 2,400000,000000$ or 2400,000000 dynes per sq. cm. of cross-section ; so that if our wire have 1 sq. mm. ($=\frac{1}{100}$ sq. cm.) cross-section the necessary Force is 24,000000 dynes, or the Weight of about 54 lbs.

Necessarily, the greater the Extensibility the less is Young's Modulus; and it may be useful to note a few values of this modulus. Cast steel, tempered, 2,470000,000000; wrought iron, 1,960000,000000; copper, 1,030000,000000; wood, 9800,000000; leather, 171,000000; fresh bone, 226000,000000; tendon, 16000,000000; nerves, 1790,000000; living muscle at rest, 93,200000; arteries, 5,100000. Thus it will be seen how much less force is necessary to stretch an artery than to stretch a rod of steel of the same thickness to the same extent.

But we must carry this matter a step farther. Young's Modulus in any substance is also known as the **Coefficient of Resistance to Extension** of that substance. Young's Modulus may be said to measure, for any substance, the property of that substance which is the inverse of its Extensibility, and which may perhaps be called its **inextensibility**, its unwillingness to stretch.

When a steel wire, for example, is stretched, it pulls back. When we hang a heavy mass on a steel wire there is at first a yielding, a certain amount of "give," for the wire stretches; but presently there is equilibrium and **rest**: the heavy suspended mass of course tends to sink, for its **weight** tends to pull it down: but this tendency is balanced by the **upward Pull** exerted by the wire which refuses, as it were, to stretch any more unless a greater stretching Force be applied to it. Then, the Reaction or back-pull or **Resistance** to any farther stretching is **equal** to the **stretching force** which that resistance balances; and the Resistance per sq. cm. of cross-sectional area of the wire is then equal to the Traction. But the Traction is equal to the Elongation × Young's Modulus. Therefore the Resistance, per sq. cm., is equal to Young's Modulus multiplied by the proportionate Elongation. Young's Modulus thus serves as a means of measuring what this Resistance will be: and hence it gets the name of the Coefficient of Resistance to Extension.

Similarly, the fraction $\frac{1}{\text{Compressibility}}$ is called the **Resistance to Compression**; and it also goes by the name of the **Elasticity of Volume**.

Again, the fraction $\frac{1}{\text{Shearability}}$ is called the **Rigidity**, or the **Resistance to Transverse Distortion.**

Lastly, the fraction $\frac{1}{\text{Torsibility}}$ is called the **Resistance to Torsion** of the wire or fibre concerned.

The condition of **equilibrium** between a Force applied and the Resistance ultimately developed in presence of the action of that force is **not** attained **instantaneously.** When we press in a spring, as for example that of a spring-gun, we find that it is very easy to move it during the first part of the movement; but it is not so easy to send it right home. The Force which we have to exert increases as the arm travels; for the Resistance which it has to encounter goes on increasing until it attains its maximum value, equal to the greatest force which we have to exert.

The Work done in producing a Deformation is always equal to the **average resistance** overcome into the **space** through which it is overcome.

Thus the Work done in stretching a bar of steel, 10 sq. mm. ($=\frac{1}{10}$ sq. cm.) in cross-section, from a length of 100 cm. to a length of 100·1 cm. is found as follows: the necessary Traction per sq. cm. is the "Elongation" ($\frac{0.1}{100}=\frac{1}{1000}$) multiplied by Young's Modulus (=2,400000,000000), and is therefore equal to 2400,000000 dynes per sq. cm. But the cross-sectional Area of the rod is not 1 sq. cm., but $\frac{1}{10}$ sq. cm.; therefore the necessary Pull upon the rod is 240,000000 dynes. This is equal to the Resistance ultimately offered by the rod to further extension: but the **average resistance** is **half** this. The **space** through which the Resistance has been overcome is 0·1 cm. Hence the **work** (=average resistance × space through which it is overcome) is 120,000000 dynes × 0·1 cm. = 12,000000 ergs, nearly one foot-pound. The same principle applies to the work done in effecting the other kinds of deformation.

Elasticity of Solids

A Solid may offer Resistance to being deformed, but yet, when it is once deformed, it *may* evince no **tendency to return** to its **normal form.** A bullet may be moulded under sufficient pressure in a bullet-mould; but once moulded it does not tend to spring back to its original shape, and it exerts no **continuous pressure** upon the mould. It is not necessary to clamp the bullet-mould down in order to keep the bullet in shape. But if a piece of **indiarubber** be treated in the same way, the **pressure** on the bullet-mould must be **maintained** in order to make the indiarubber maintain its acquired form; and the moment this pressure is relaxed, the rubber pushes the jaws of the mould apart and **springs back** to its **original form.** It therefore not only offers Resistance to change of shape, but **keeps up** that **resistance** as long as the Deformation endures: and the resistance so kept up is **equal** to the **Resistance to Deformation.** It is so, at any rate, when the deformation is not kept up too long or is not excessive in amount: but we know at the same time that we cannot rely even on a watchspring retaining its springiness if we keep it habitually wound up too tight, or if we allow a watch, wound-up but stopped, to lie about for an indefinite period of time. If, however, the **pressure** which the deformed body persistently keeps up were to remain **steadfastly** and constantly **equal** to the Pressure which had caused the deformation, or to the Resistance (that is, to the ultimate resistance) offered to deformation, we would say that the body is "**perfectly elastic.**" If the pressure so kept up by the deformed body be from the beginning, or if it after some time become, **less** than the deforming pressure, we say that the body is "**imperfectly elastic.**"

A perfectly elastic Solid, therefore, will perfectly regain its shape when distorted: and in order to distort it, a certain Force or Pressure or Torque must be exerted; the body itself opposes a certain Resistance to deformation: and once deformed it must be kept in its acquired form by the **continuous** application of a force or pressure or torque, which is continuously neutralised by the counter-force or counter-pressure or counter-torque exerted by the distorted body itself.

An ivory **billiard ball** is very **slightly deformed** by an impact; and it is very nearly **perfectly elastic**, for it almost perfectly regains its original shape. The amount of its deformation may be ascertained by dropping it on a paint-smeared slab: the paint will spread over a certain area of the ball.

On the other hand, an **imperfectly elastic** body, when subjected to a given deformation, does not tend to reverse or undo that deformation completely when left to itself. After being distorted it may, therefore, spring back to something more or less resembling its original form, but always retains a certain amount of the deformation imposed upon it.

There is probably **no substance** which is **absolutely perfect** in its Elasticity: all substances tend to remain somewhat **distorted** after being once put out of shape: but many substances, such as steel or indiarubber, can be bent very much out of shape and yet tend to spring back so nearly to their original shape that, for all ordinary deformations, we cannot distinguish their newly-acquired shape (after the deformation and elastic restitution of form) from the original shape. Still, there is always a limit to this: if we distort anything too much it will fail to regain its original shape. Hence we say that bodies have **Limits of Elasticity**: and by this we mean that there are, for each object or substance, certain Limits of Distortion within which the Restitution of Form is practically if not absolutely perfect, and beyond which the restitution is markedly and distinctly imperfect.

A strip of steel has wide limits of elasticity: it may be bent upon itself a good deal before it will fail, when let go, to regain its original form: but a strip of lead has very narrow limits of elasticity, for a very slight amount of bending is sufficient to impart to it a permanent deformation. Still, even a strip of lead is not wholly without elasticity: if it be *very* slightly deformed, it will oscillate and vibrate when let go: and thus the difference even between lead and steel is a question of degree only.

When the elasticity is **perfect**, the elastic restitution-pressure is equal to the resistance to deformation; and hence Young's Modulus, the Coefficient of Resistance to Compression, and the Coefficient of Rigidity, all serve as means of measuring the Forces exerted by **perfectly elastic** bodies deformed in the appropriate ways: whence these terms are often called by one and the same name, the Coefficient of Elasticity. This seems, however, somewhat confusing.

Applications of Elasticity.—The property of Elasticity is one which is utilised in a great variety of ways. For example, we may contrast the **rough jolting** of a cart without springs, or of a railway carriage with springs which are too stiff, with the **smooth motion** of a carriage poised on good flexible springs. In general, it may be pointed out that an impulse given through an **elastic intermediary** is not spent in shattering or jolting the body acted upon: and thus, if we tie a string round a heavy mass of iron and pull sharply upon the string, we may snap the string without making the heavy mass of iron move; whereas if we arrange an indiarubber band between the string and the mass of metal, and then sharply pull upon the string, we find that first of all the rubber band is stretched, and that then the rubber band tends to come back to its original length, and the heavy mass may be lifted without causing any detriment to any part of the contrivance put in action. In the same way, if a patient have a **limb** put under **extension** by means of a heavy mass suspended by a cord passed over a pulley, and if that limb undergo a muscular twitch considerable pain may be induced by the jerk; but if there be a spring between the limb and the suspended mass, the twitch first extends the spring a little against a gradually but continuously increasing Resistance, and then, when the twitch has ceased, the heavy mass is slightly lifted and gently let down again while the spring returns to its normal length, so that the resultant movements are all smooth. How far any such movement, the consequence of a muscular twitch, can be permitted at all, is of course a question for the surgeon in any particular case.

In all kinds of apparatus we find elasticity applied. In **bulldog artery forceps** the steel is so fitted up that it tends to press the blades firmly together: when the blades have to be separated, the forceps are pressed by the fingers and thumb: but when the separating pressure is relaxed, the instrument springs back to its original form, and can thus be made to take a firm and tenacious grip of anything—an open artery—laid between its jaws. In **scissors**, too, there is often a spring to make the blades separate spontaneously as soon as the pressure of the hand is relaxed.

Again, a spring is very frequently used in order to keep **loose parts of apparatus** in contact with one another. Thus **spring-clips** are used in order to keep microscopic object-slides in contact with the stage of the microscope, or to secure them in position when the microscope is tilted back or laid horizontally. In the **fine adjustment** of a microscope a spring is used in order to **prevent** there being any **play**, such as would cause the parts of the mechanism, actuated by the screw, from lagging behind when the fine screw is rotated. The fine screw drives a part of the mechanism against a spring, in which case the part of the mechanism so driven cannot travel faster than the propelling screw: or the screw acts along with the spring, in which case the spring expands and enforces prompt and ready obedience to the movement of the screw. In both cases the spring keeps up a persistent pressure, and the movable parts of the apparatus have their relative position rigorously determined by this pressure, so that there is no scope for any irregular play of movement between them.

The tendency of an **indiarubber ball** to regain its form when squeezed is most useful in many forms of apparatus, as in the indiarubber caps or balls of **pipettes**, of **fountain pen** tubes, of **suction nipples**, of **spray producers**. The restitution of form tends to produce a partial vacuum or a defect of air-pressure within the ball: and it takes place until the tendency to elastic restitution *plus* the partial air-pressure within the ball are together equal to the externally acting atmospheric pressure. There will not be complete restitution of form unless the internal and external pressures are equal. If such a ball be surrounded by a **vacuum** while the Atmospheric Pressure acts within it, it will tend to **dilate** and to fill up the vacuum; and this is the normal condition of the **lungs** themselves, which are dilated by the Atmospheric Pressure so as to fit the chest walls, though these are normally too large for them.

In **spring mattresses** each local spring yields to a different extent, according to the share of the aggregate Weight which falls to its lot to support. A spring mattress with independent springs, therefore, assumes a shape which fits the body: but it does not produce an equal intensity of pressure all over, as a water-bed or an air-bed does.

In **trusses** we see the **torsional** elasticity of steel applied; and in the **pessary** we see the continuous application of pressure by the elastic material persistently tending to regain its original form when distorted.

Even the elasticity of **hair** has been made use of in some delicate apparatus, for it tends to straighten out if bent; and for many purposes a feeble spring made of a bent slip of **paper** is very useful.

In the **arteries** there are circular **elastic fibres** which tend to bring the vessels back to normal diameters when dilated by a cardiac impulse, and which cause the arteries to remain as open tubes when they are cut across. In the **crystalline lens** of the eye there is elasticity: the lens is kept thinner and flatter by the continuous tension of the suspensory ligament: but when this is more or less relaxed, the lens succeeds, more or less, in regaining a thicker and more convexed form. In the great ligament at the **back of the neck** the elastic fibres are very much on the stretch, and the head is thus sustained against its normal tendency to fall forward. The **intervertebral cartilages** are very elastic, and tend to prevent direct shocks being carried to the brain; and the **ribs** and **costal cartilages**, which undergo both flexion and torsion, are also very elastic.

The ligaments of a **lamellibranch shell** tend to keep the shell open, and act in the shell as a piece of indiarubber would do if fitted between a door and its frame, near the hinges: the animal, so long as its shell is shut, is engaged in keeping it shut, and when it lets go the shell opens. In the **tracheæ** of **insects** an elastic spiral keeps air-supply tubes open, as a steel spiral does in **rubber gas-pipes**. In the **trachea** and **bronchi** of man elastic rings serve a similar purpose.

Elasticity may also be applied as a means of **transmitting energy**. In the ordinary case of transmission of power by a long **steel shaft**, which is set in rotation by a flywheel, and which at its other end sets the axle of a machine in rotation against a Resistance, either directly or through the intervention of belting, the shaft itself is supposed not to twist; but there is hardly any case in which it does not twist to some extent: and its tendency to recover its original untwisted form causes it to overcome the Resistance offered to its rotation, and thus to keep up a rotation which keeps pace with the rotation of the flywheel. The same principle may be applied in an exaggerated form, as when the shaft is reduced to a **spiral of steel wire**. The actual twist of the end remote from the driving wheel may in this case be considerable; but once this twist is set up, the actual rotation against resistance tends to keep pace with the rotation of the driving wheel. This form of shaft, if such it may be called, presents the advantage of being **flexible**; such a spiral spring may be bent to any extent without interfering with its power of transmitting rotation; and this means of transmitting rotation is utilised in the tooth-drilling apparatus of **dentists**, as also in a particular form of **screw-propeller** applied to small boats.

Elasticity plays also a useful part in the transmission of Energy by means of the use of an elastic intermediary, when the source of energy is itself fluctuating in its character.

A horse pulling a car, for example, is not a uniformly acting motor; it gives a tug at each stride. But at each tug it gives the car a certain jerk or jolt; it is itself pulled back by this: and the result is painful. Any one may verify this for himself by harnessing himself to a heavy hand-cart and pulling it rapidly across a rough pavement. If however a spring be interposed between the horse and the car, at each tug the horse pulls upon the spring; the spring then pulls upon the car: the jolts are transformed into a series of gently undulating increases and diminutions of the pull upon the car, which accordingly runs more smoothly. When a car, fitted with a spring in this way, is running, the spring can be seen to be continually lengthening and shortening. Professor Marey found that the average pull upon the car was much less when a spring was used as an intermediary than when there was none; and the Energy expended by the animal was 20 per cent less. Elasticity also plays an important part, for similar reasons, in ambulance cars.

Vibrations.—When an elastic body is deformed and let go, it does not, as a rule, simply return to its original form and come to rest at once. It usually swings past its original form and becomes deformed in an opposite sense or direction.

Let us take a strip of steel and secure one end of it in a vice: if we pull the free end aside so as to bend the strip, it will tend to carry back the finger: if we relax the pull gently, we find the strip gradually assuming its original form and then stopping: it has then no Energy stored up in it, for it has done as much Work in pulling the hand as the hand had done upon it, in the first instance, in pulling it out of shape: it therefore comes to Rest. On the other hand, if while it is distorted we suddenly let it go, it springs back, but passes through its original form with great Velocity: at the moment of passing through its original form the Energy which was stored up in it, in virtue of its distortion, as potential Energy, now appears as kinetic Energy; it goes on until it is distorted so far as to store up that energy as the potential Energy of an opposite distortion.

But it cannot retain the oppositely distorted form: it swings back: it again overshoots the mark: and this is **repeated** over and over again. The **force** impelling towards the original or median position or form is always **proportional** to the **displacement** or distortion : hence the conditions are those that give rise to **Harmonic Motion.**

A **tuning-fork** has its two limbs alternately approaching and receding from one another : its vibration is due, in this way, to the elasticity of the steel ; and since the conditions are those which give rise to Harmonic Motion, the successive vibrations are effected in equal times, whether they be ample or of small range.

When a displacement and a corresponding vibration have once been set up in any part of a solid, a **wave** is set up which is propagated along or through the solid. The rate of propagation of this wave-motion depends on whether the original disturbance was itself compressional-and-rarefactional or transverse in its character.

A tuning-fork, once set in vibration, gradually **dies away** in the amplitude of its vibrations. In the first place there is a drain upon its Energy in the production of Sound ; it does **work** upon the **air** and loses Energy to a corresponding amount. But even in a vacuum the vibrations of a tuning-fork will gradually wane away, its oscillations becoming more and more restricted ; the waning away is not so rapid as in air, but still is distinct. The reason of this is that the substance of the tuning-fork itself offers Resistance to the oscillation of the fork : and this property goes by the name of the **viscosity** of the **solid.** The consequence of this is that at each successive transit through the mean position, a greater and greater proportion of the whole original Energy imparted to the substance during the original deformation has become converted into **heat**, and the oscillations die away : they do not become less frequent, but they become less ample until at length all evidence of them disappears. Steel presents little of this so-called Viscosity : lead presents much of it : whence a tuning-fork made of lead sounds for a very short time, while one made of steel will continue to sound for a much longer time. And curiously enough, if a tuning-fork of steel be compelled to keep up its vibrations for a very long time it may become very viscous, and may stop at once when the exciting cause is removed: the steel as it were becomes thoroughly tired of vibrating: and this phenomenon is known as the **fatigue of elasticity**.

There seems to be some **molecular change** undergone during the oscillations: and this can be recovered from if the steel be allowed sufficient rest: but if there be not sufficient rest allowed, the steel becomes viscous or even brittle, and may snap when subjected to vibratory stresses far less than it could at first have sustained with impunity. The same kind of thing is seen in **railway axles** which are exposed to much vibratory jarring: they may even become crystalline and brittle: and an **iron bridge** which may stand the passage of a limited number of trains per day for a long term of years may not be able to recover from the vibratory stresses induced, at too frequent intervals, by too great a number of passing trains, and may thus become brittle and give way.

Strength of Materials

Strength of materials depends both upon their substance and their form, and also upon the direction in which force is applied. To take the simplest instance, a rod of a substance may have a heavy mass suspended upon it; but if the Weight of the suspended mass exceed a certain limit, the rod will **snap**. The greater the thickness of the rod, the greater (in direct proportion to the cross-sectional area) will be the Weight which the rod can stand. For the sake of comparison, however, the standard dimensions of the rod will be one square cm. of cross-sectional area; a rod of a given substance one sq. cm. in cross-sectional area will be able to stand a stress equal to the Weight of so many grammes of matter, but can stand no more without snapping: and this number of grammes is, for each substance, the "**breaking weight**" of that substance.

Different substances vary very much in their breaking weights: and the following are a few examples. Steel pianoforte wire, 22,120000 grammes per sq. cm.: bone, from 1,500000 to 430,000, with an average of 800,000; tendon, 625,000; nerves, 135,000; veins, 18,500; arteries, 13,700; muscle, 4500.

Conversely, if heavy masses be laid upon a block of a substance, or if Pressure be by any equivalent means applied to it, it may be **crushed**: and the mass whose Weight will bring about this result in a cubical block, each of whose dimensions is 1 cm., is the "**crushing weight**" of the substance experimented on.

Substances may also be broken by trying to **bend** them, or by subjecting them to conditions in which if they had been flexible they would have bent. Substances which "break rather than bend" are said to be **brittle**; substances which bend under a transverse force applied to them are said to be **flexible**, like the gum elastic used in catheters; and substances which retain their form without bending are **rigid**.

A short glass rod can be readily broken by the two hands: a glass fibre of the same length or an extremely long glass rod can readily be bent to a considerable extent; the short glass rod is not absolutely devoid of flexibility, but before it could become materially bent, the stretching of one side and the corresponding compression of the other would be considerable; so the rod does not come to bend to any material extent, but snaps. The glass fibre, on the other hand, can be bent through a considerable angle before its opposite sides or aspects become, to any material extent, elongated or shortened by the process of bending. As a rule, an object does **not break** if it is **flexible**. Contrast a **pancake** tossed in a pan with a **china plate** falling on the floor; the Forces are similar. If the pancake fall on its edge, it bends as it sinks into its new position: the china plate tends to bend in the same way, but it cannot bend; it snaps.

Let a person fall with outstretched arm, but in a state of muscular relaxation, as in a fit or in a state of intoxication, and let us suppose that the hand reaches the ground first: when the fingers touch the ground the hand rotates on the wrist so as to come to lie flat on the ground: the forearm rotates at the wrist-joint so as to come to do the same thing: the upper arm rotates freely upon the elbow-joint so as to come to lie flat upon the forearm: and by this time the falling person has sunk upon the ground, with his arm limply folded under him. If, on the other hand, he falls with a conscious effort to save himself, the outstretched arm has its muscles contracted and the joints are fixed, so that the arm as a whole is stiff: it may in this case readily happen that some of the bones of the limb are snapped across.

Masses which are readily deformable are thus not readily broken; and if they be at the same time elastic, they may be exposed to considerable violence without detriment.

Again, masses may be so built up as to offer a maximum of resistance to bending or crushing. A rod of metal, for instance, is more easily bent or crushed than the same quantity of material disposed in the form of a **tube**, so long as the walls of that tube are not too thin. Hence we find, as combining lightness with strength, that the **stems of plants**, the **feathers** of birds, and the **long bones** of the body are tubular: and we see in mechanics that this principle is frequently applied, as in the framework of **bicycles**.

Further, when rigidity is desired, a **lamellated** or **trabecular** structure is often of advantage.

We see this in **lattice-girder bridges**, in which some bars ("stays") are in tension, while others ("struts") are exposed to compression: and bridges so made can span distances which solid bridges could not fetch, for these, even if we could suppose them to have been built, would collapse through the effect of their own Weight. In the spongy structure of **bones** the same thing may be seen. In the upper part of the **femur** it is necessary that the Weight of the body should not deform the bone: and accordingly we find an arrangement of trabeculae in which horizontal stays, oblique struts, and vertical stays form a framework, which transmits the weight to the shaft of the bone below, much after the fashion of a "lanterne" lamp-post. In the **astragalus** we have a comparatively light and porous structure, but the trabeculæ are so arranged as to resist and distribute the Weight of the body and the counter-pressures from the ground, which are transmitted by those bones, the os calcis and the scaphoid, that abut against the astragalus in the arch of the foot.

CHAPTER V

SOUND

THE phenomena of **Sound** are due to **vibrations** of **elastic** bodies, solid, liquid, or gaseous, and to the **propagation** of compressional-and-rarefactional **waves** in **elastic** media ; and were it not that we have special sense-organs, the **ears**, for the detection of these vibrations and waves the whole Theory of Sound would form merely a part of ordinary Kinematics or Mechanics. As it is, however, the subject possesses an importance which the study of vibrational motion and wave-propagation, in ordinary elastic materials, might not of itself have possessed.

Let us take an ordinary **tuning-fork** and set it in vibration in the ordinary way, by striking it on the knee, or by drawing a violin-bow across it, or by drawing a piece of stick through it between the prongs. We hear a **sound** ; and we are able to note that the sound produced is a musical **note** and not a Noise ; that it has a certain definite **pitch** ; that it has a certain **loudness**, which in the beginning depends on the force with which the fork is set in vibration, and which gradually wanes away ; and that the sound is the **characteristic** sound of a Tuning-fork, not of a violin, a flute, a human voice, etc. Sounds, as produced, may therefore differ in Purity, in Pitch, in Loudness, and in Character.

If we examine the tuning-fork while it is originating a sound, we find that it is in **vibration**. This we may ascertain by applying the prongs to the lips, to the teeth, to the surface of water, to a piece of glass; or by bringing the tuning-fork into contact with a pith-ball suspended by a thread, or by bringing it up under a match or splinter of wood laid across two points of support. The tuning-fork vibrates as an **elastic mass**, as a whole, and not in its molecules. The effect of the alternate approach and recession of the prongs towards and from one another, is alternately to press upon the surrounding air and to withdraw from it. The **air** in the neighbourhood of the fork is thus **alternately compressed** and **rarefied** by the movement of the flat surfaces of the prongs. Such alternate compressions and rarefactions of the air, in consequence of Vibration, result in setting up **waves in the air**, which travel outwards from the source of disturbance.

The Waves in the air strike upon a membrane in the ear of the listener, the **drum** of his **ear**, his *membrana tympani:* and this membrane is set in **motion** by the waves. This Motion **corresponds** to the original movements of the tuning-fork; and the motion of the membrane sets certain bony and liquid mechanism **within the skull** into a corresponding state of movement. This shakes particular **nerve-ends**, and causes **stimulation** of these; and the nerves connected with these convey impressions to the **brain**, which then experiences a particular **sensation**. Our **experience** of what we have heard on previous occasions enables us to **identify** the particular Sensation experienced, in the present case, as that associated with the sounding of a **tuning-fork**.

If any part of this chain—the vibrating body, the waves in the air, the movement of the drum of the ear, the movements of the auditory mechanism, the efficiency of the auditory nerve-ends, the efficiency of the auditory nerve-strands, the efficiency of the brain in response to the stimuli communicated to it—should happen to break down in any way, or if the connection between any two of its links should fail, we would hear no Sound. With the later terms of this series we have nothing to do in this volume; but the earlier terms are purely physical in their character.

Air-waves may **fail** to reach our ears through there being **no air-waves set up**, and that for various reasons. *First:* let us suppose our vibrating or sounding body is supported on wadding in the **exhausted** bell of an air-pump. There is **no air** to be alternately compressed and rarefied in the neighbourhood of the tuning-fork; and further, the vibrations of the fork are not communicated through the wadding to the baseboard of the air-pump: so no air-waves are produced, and there is no Sound heard. *Second:* if the air be only **partially exhausted**, the effect may still be the same or nearly the same, for it is not easy in that case to set up Waves of compression and rarefaction in the air; the air prefers to **flow back-and-fore** round the fork at each oscillation, surging round the fork, but not having any waves set up in it. *Third:* even in ordinary air a result quite similar to that of the last case will ensue if the sounding body be **too slender**.

For example, if a string be stretched between two points in the open air, say across a corner between two brick walls, and if it be plucked or bowed with a violin-bow, the sound heard will be extremely faint; the air is not effectively compressed and rarefied by the vibrating string, but flows or surges round it back-and-fore.

If instead of rarefied air we have a **light gas**, such as Hydrogen, the result will be similar; a **feebler sound** is produced when the sounding body is made to vibrate in hydrogen than when it vibrates in ordinary air, for the hydrogen has a greater tendency to surge back-and-fore round the fork, and not to undergo effective compression.

If, however, we vary our experiments in the contrary direction, and produce **more effective compressions** and rarefactions of the air by the vibrating body, we get **louder sounds**.

If we have a bell or tuning-fork sounding in a receptacle, and **compress the air** in that receptacle, the sound will become louder: a watch seems to tick very loudly in a submerged diving-bell; the air round the vibrating body is denser and more massive, and has correspondingly greater **inertia**, so that it does not so readily flow away to one side; it is therefore the less able to evade the compression and rarefaction imposed upon it. If we suspend our vibrating string with one end attached to the **panel of a door**, and set it in vibration, the sound produced will be very loud; but it will appear to come from the **door**, not from the vibrating string. The reason is, that the vibrations of the string give the door-panel a corresponding series of alternating pulls and releases; the **panel** itself **vibrates**; and its vibrations act upon the air near the surface of the panel. That air cannot move out of the way in time; and it is effectively subjected to alternating compressions and rarefactions by the alternating movements of the door. The door thus acts as what is called a **sounding-board** to the string: and though the amplitude of its vibrations is small, its action upon the air is very efficient, so that the Sound produced is very loud. The same principle is applied in the sounding-board of the **pianoforte**, and in the belly of stringed instruments such as the **violin**: and the experiment may readily be tried, of listening to the sound produced by a **tuning-fork** suspended by a string in the air, and to that produced by the same tuning-fork with its shank pressed against the panel of a door.

In the **speaking trumpet**, which is a conical tube, the mouth is applied to the smaller aperture, and words are spoken; the conical tube prevents lateral flow and reflow at the mouth of the speaker, and makes the resultant air-waves broad-fronted at the broad mouth of the trumpet.

The **slower** the vibration, the greater is the tendency to **lateral flow and reflow**; and on the other hand, the more rapid the vibration the less necessity is there for breadth in a vibrating body. This is illustrated by the chirping or **stridulating organs** (two toothed bars and a sounding-board) of certain insects; these, though very small, act so rapidly—some 12,000 complete oscillations per second—that they effectively compress and rarefy the air without allowing it time to flow round.

It is not absolutely necessary that the means of propagation of the vibration from the vibrating body to the listening ear should be the intervening Air. The **vibrations** may be **communicated** through **solids**, through

liquids, or through **gases** other than air. Each such medium has its own **Velocity of Propagation** of sound-waves, which is the same thing as the Velocity of Propagation of compressional-and-rarefactional Waves in the particular medium.

For instance, in **air** the **velocity** is about 33200 cm. or 1089 feet per second (at 0° C.), and sound-waves take one second to travel 33,200 cm. Accordingly, if we see a **lightning flash**, and then have to wait say five seconds before we hear the **thunder** begin, we know that the source of sound is five times 33,200 or 166,000 cm. away; a little more than a mile distant.

The velocity in air (and in other gases) is **unaffected** by variations in the atmospheric **pressure**: but it is **increased** by Heat, for it is proportional to the square root of the Absolute **temperature**: and it is **greater** in **damp** than in dry air, for damp air is less dense than dry air. In **water** the velocity is greater, being 148,900 cm. per second.

In sound-waves, as in all other cases of wave-motion, the law holds good that $\nu = n\lambda$, where ν is the velocity of propagation of the wave motion, n is the number of vibrations per second (the "frequency"), and λ the length of each wave. Thus in air, $\nu = 33200$ cm. per second; if n be 500 per second, what is the **wave-length**? Ans.—It is $\lambda = \frac{33200}{500} = 66{\cdot}4$ cm.

As an example of **propagation** of sound-waves through **Solids**, we may take the transmission of sound by the **earth**, when we lay our ears to it to listen for distant trains, distant marching, distant firing.

If one end of a long **rod of wood** be held by one end in the teeth, and if a vibrating tuning-fork be held to the other end, the sound will be distinctly heard; and the schoolboy's trick of speaking at one end of a long desk to a listener at the other illustrates the same transmission of sound-waves by wood.

In **auscultation** of the chest in medical work, it is not unfrequently found that sounds produced within the chest are conducted to regions at some distance from the points at which they originated.

In the ordinary **stethoscope** sound is conducted both along the **wood** and by the **air**. If a guitar be laid by one edge on the upper end of the stethoscope, the heart-sounds may often be heard strongly reinforced: for the guitar acts as a **sounding-board**.

The Transmission of Wave-motion, which is purely mechanical in all cases, is obviously so if we rest the shank of a vibrating **tuning-fork** against one end of a **long wooden rod** and bring the other end of that rod into contact with a **door**: the Vibrations propagated from the tuning-fork to the door, along the wood, cause the door to sound out loudly. Sound-waves readily run along **metal wires** or along **stretched threads.**

In the ordinary **toy telephone**, two membranes stretched across rings have their midpoints connected by a stretched silk thread: when the one membrane is spoken to, the air-waves set it in vibration, and the vibrations are communicated along the silk threads, with the consequence that the other membrane is made to vibrate in a manner corresponding to that of the first membrane; then it acts as a sounding body, compressing and rarefying the air in the neighbourhood of its opposite face, and the listening Ear hears the original sound reproduced. More elaborate apparatus of this kind, in which the parchment membranes are replaced by heavier wood discs and the silk threads by wires, will reproduce Sound in this way at great distances.

The actual **amplitude** of vibration of such discs need not be great; an oscillation through no more than the ten-millionth part of a centimetre is quite sufficient for the production of audible sound, if the ear be held close to the vibrating object.

In **Strebel's stethoscope**, its chest-end is closed by a membrane, which carries a little pointer: this pointer touches the chest-wall and compels the membrane to take up vibrations the same as those of the chest-wall. On the other side of the membrane is a closed cavity containing air, and running through the body of the stethoscope to the ear-end, where it is terminated by a second membrane. This membrane is set in vibration similar to that of the first, and the observer's ear, placed near it, hears the chest-sounds.

In **Liquids**: **divers** while under water hear the sound of waves beating against the shore; and on an **ice-floe** the sound of an approaching storm can be heard by applying the ear to the ice. Waves of Sound can be produced by blowing an **organ-pipe** under water: the organ-pipe acts under water just as it would in air; and to the listening ear the surface of the vibrating water acts as a sounding body.

In the **open air** the waves, unless confined to narrow channels, are **spherical**, spreading equally in all directions when the source of sound is so very small that it is practically a **point**.

When the upper strata of the air are cooler than the lower, the sound-waves travel more rapidly in the lower strata, and the **wave-front** is **bent upwards** and may pass over the head of the listener, so that he may not be able to hear the sound. When the upper strata are warmer, the sound tends in the same way to **descend**. When **wind** blows, the upper strata generally move more rapidly, and the wave-front is made to bear **downwards**, so that in particular positions to windward the sound may be very distinctly heard, sometimes at a great distance.

The production of **loud sound** is associated with great mechanical disturbance of the air; the firing of a **cannon** may break windows, through the impact of the **air-waves** produced.

Air-waves are made to do actual **work** in **Edison's phonomotor**; in this instrument a membrane is stretched over a frame; at its posterior surface it is connected with a broad hook which rests on the broad margin of a heavy wheel: the margin of this wheel is provided with roughnesses so shaped that it is easy for the broad hook to slip over them in one direction, but in one direction only. The membrane is spoken at; it vibrates; the broad hook slips over some of the roughnesses, and on its return gives them a backward pull; this process is repeated at each vibration, and continuous sound causes the heavy wheel to rotate with considerable speed.

Air-waves are **reflected** by a smooth dense obstacle, according to the ordinary laws of **Reflexion** of **Waves**.

Sound can therefore be reflected by a **mirror**: and a small bell ringing round the corner of a house can be rendered audible by a sufficiently large mirror, placed at a proper angle in reference to the sounding bell and to the listening ear. Air-waves can even be reflected, to some extent, by a **stratum** or column **of air** differing in density from the surrounding air; hence sound is partly reflected at the surface of each of the ascending and descending columns of hotter and colder air which exist even during apparently clear weather. In **foggy** or even in rainy weather the air may be **more uniform** than in clear weather; there is then **less** of this **reflexion**, and less dissipation of the sound, so that in such weather sound may actually travel farther. Air-waves may be reflected from the **walls** or the **roof** of a building: and if these be so shaped that the reflected air-waves **converge** upon some point other than that from which the sound-waves start, a listener situated at that point will be able to hear what is said. This occurs mostly when the roof is ellipsoidal and vaulted, or the walls elliptical: a sound produced at the one **focus** of the ellipse can be distinctly heard at the other, for the air-waves are reflected to that point. The most familiar case of reflexion of sound-waves is the ordinary **Echo** from a broad cliff or wall. The sound-waves, travelling at 33200 cm. (1089 feet) per second, are reflected; and if a person speak in the presence of a cliff or wall at the distance of say 1660 cm. (54·45 feet) and at the rate of ten syllables a second, by the time he is beginning the second syllable the series of reflected waves corresponding to the first syllable begins to reach his ear, having travelled 3320 cm. (108·9 feet), to the cliff and back, during the tenth part of a second. If the sound be reflected several times, to-and-fro from cliff to cliff, there may be a **Multiple Echo**, which repeats a syllable or sound several times.

When the reflecting surface is **too near** to form a distinct **echo**, the effect becomes merely a **reinforcement** of the sound produced; as in the case of sounding-boards behind and above pulpits and orchestras.

Sound can even be **refracted**, as for instance by a large lens made of two sheets of collodion cemented at their edges and inflated with carbonic acid. Such a lens brings sound-waves, say from a ticking watch, to a focus on the other side of it.

If the superposition or **interference** of air-waves results in Rest, or in comparative quiescence, at any one point, there will at that point be no sound, or but little sound heard.

If two tuning-forks, not exactly in unison with one another, that is, not vibrating exactly the same number of times per second, be sounded together, as they vibrate they sometimes **concur** in their direction of motion, and then come to be more and more **opposed** to one another: they thus pass through alternate stages of concurrence and opposition. The consequence is that the listening ear perceives **fluctuations** in the **loudness** of the sound produced. Suppose one of the forks vibrates 513 and the other 511 times a second; the result is as if the vibration were at the rate of 512 per second, with a maximum and a minimum of loudness twice (=513 - 511) every second. These fluctuations are called **Beats**.

If in Fig. 68 A and B represent two apertures in the side of a padded box, within which a whistle or organ-pipe or bell is caused to produce sound, the ear placed successively at *a*, *b*, *c*, etc., perceives alternate sound and silence; for in these successive positions the waves, from A and B respectively, alternately aid and thwart one another.

Sound-waves in air are generally long enough to be **large** in comparison with the **obstacles** they encounter, or the **apertures** through which they pass. When this is the case they pass **round corners**, and the listening Ear can hear the sound though the Eye may not be in a position to see the source of sound (see Fig. 48). But where the waves are very short, as they are in the case of very high-pitched sounds, the obstacles they encounter or the apertures through which they pass may be large in comparison with them; and in such cases the Sound may fail to come round corners, and there may be distinct "**sound-shadows**" similar to, but not as sharp as the Optical Shadows produced if the source of sound were replaced by a source of Light (see Fig. 69). In order to hear all the sound produced, the listeners to music ought therefore to be in full view of the orchestra.

Sources of Sound.—In a **violin string** or a banjo string played in the usual way, the vibrations are **transversal**, as may be seen on looking at the string when vibrating: each point of the string vibrates across the line of the string itself. The vibration is of the kind previously described as **Stationary Vibration** (p. 47).

If we assume the string to be perfectly flexible, and to be tightened up by a pull or Traction of t dynes per sq. cm. of its cross-sectional area, the Frequency, n oscillations per second, is $n=\sqrt{t/\rho}\div 2l$, where ρ is the density of the string and l its length. If we suppose the stretching Traction to be exerted by, or to be equivalent to, the Weight of m grammes of matter hung on the string, or pulling upon it over a pulley as in Fig. 122, this equation takes the form $n=\{17\cdot 67\sqrt{m/\rho}\div ld\}$ where d is the diameter of the string. This formula enables us to work out a great variety of problems relating to vibrating strings.

If a wire of steel (density $\rho=7\cdot 8$), 1 metre long ($l=100$ cm.)

and 1·2 mm. thick ($d=0·12$ cm.) is stretched by the weight of 40 kilogrammes ($m=40000$ grammes) and set in transverse vibration, what will be the **frequency** of its fundamental vibration? Ans.—$n=17·67 \times \sqrt{\frac{40000}{7·8}} \div (100 \times 0·12) = 105·45$ vibrations per second.

The Number of Transverse Vibrations per second depends: (1) *inversely* on the **length** of the stretched string; (2) *inversely* on its **thickness**; (3) directly on the *square root* of the **stretching force** applied; (4) *inversely* on the *square root* of the **density** of the material of the string (or wire). All this can be verified with the aid of the **Monochord**, coupled with the knowledge otherwise derived (p. 214), that the number of vibrations per second, n, is told us by the **pitch** of the Sound produced.

The Monochord is a box of light wood containing air. Its lower side is open, and there are two apertures on each side laterally. Upon this box rest two bridges ("banjo-bridges"), one near each end. Over the bridges are stretched a couple of wires; both are passed round pegs at the end A; the other end of the one is connected with a **tuning-peg**, which may be turned by a pianoforte-tuner's key; while the corresponding end of the other is passed over a pulley and made to support a **weight**. We may use a **movable bridge**, slipped up and down under either wire so as to limit the portion of it which is free to vibrate, and we may thus vary the **length**, l; we may vary the **thickness**, d, by fitting up different wires successively of the same material; we may vary m by altering the **load** at B; we may vary the **density** ρ by fitting the apparatus up with wires of different materials; or we may vary any or all these terms at the same time. The formula above given always applies, so that if we know any four of the terms n, l, d, m, and ρ, we may find the fifth by calculation.

Fig. 122.

In the case of the reeds of a Harmonium or Concertina, or in the prongs of a Tuning-fork, we have "**rods**" fixed at one end and freely swinging their free ends. The Rigidity of the material comes very much into play; and the general rule is that the **Frequency** is directly proportional to the **thickness** and to the *square root* of the **Young's Modulus** of the material, and *inversely* proportional to the *square* of the **length** and to the *square root* of the **density**. From this it follows that if we have two tuning-forks of the same material and the same shape, but differing in size, the Frequency is *inversely* proportional to the **linear dimensions**, so that a 2-inch fork will vibrate twice as often in a second as a 4-inch one.

Tuning-forks may be made to vibrate more **rapidly** by **filing** their free **ends**; more **slowly** by **thinning** their prongs near the base. Their speed may also be regulated by slipping **clampers** up and down their prongs: the nearer these are to the free ends, the slower is the vibration.

Discs of metal, glass, etc., can be made to vibrate by means of a violin-bow drawn across their edges. If sand and lycopodium be strewed upon them, the sand collects on certain lines of comparative rest, while the lycopodium is blown by the air-currents into places where the vibration is most active: the former are the **nodal lines**, A, B, etc., Fig. 123; the latter are the vibrating sectors between the nodal lines. When the ear is held immediately over a vibrating sector, say over C, or better, if a tube be led from near C to the ear, a loud sound will be heard: at A, B, etc., no sound will be heard: at O no sound will be heard, for the alternate segments swing in opposite directions and neutralise one another's effect upon the air above O, so that this air remains at rest.

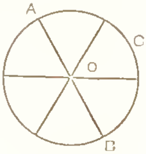


Fig. 123.

In a **drum** we have a parchment membrane stretched tightly and equably round a rim. When struck the membrane vibrates as a whole, and its frequency is *inversely* as its **radius** or diameter, and directly as the *square root* of the **tension** to which it is exposed. If a Membrane be **not equally stretched** in all directions, it would vibrate feebly in the direction in which it is least stretched, and forcibly in the direction in which it is most so. It comes to act like a number of cords laid side by side, and cemented together so as to form a sheet: the sheet as a whole vibrates with the same frequency as each component cord would have done, under the same tension per unit of transverse-sectional area. This is of importance in reference to the mechanism of the Ear.

When a **bell** vibrates we have two simultaneous modes of vibration: the bell divides into sectors: these sectors alternately **dilate and contract** radially, while contiguous sectors are in opposite phases of vibration, as shown in Fig. 124. At the same time there is an alternating **twisting** oscillation of the bell: the nodal lines, down the bell at A, B, C, D, are the parts most subject to this twist; and the parts which dilate and contract most are those at which there is the least twisting movement.

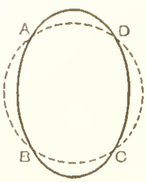


Fig. 124.

In this twist A and C would twist in the same direction round the circle, while B and D twist in the opposite direction.

If we draw one point of a violin-bow along a stretched string, we cause a **longitudinal vibration** of very high frequency: the sound produced is very shrill. The particles oscillate to-and-fro in the line of the length of the string.

The Frequency is $n=\frac{1}{2l}\cdot\sqrt{\frac{\mathfrak{y}}{\rho}}$ where l is the length of the string and $\mathfrak{y}$ is the Young's Modulus of the string. For example, if a steel wire ($\mathfrak{y}=2520{,}000000\times 981$, and density $\rho=7{\cdot}8$) of one metre in length ($l=100$ cm.) be set in vibration in this way, the frequency is $\frac{1}{200}\times\sqrt{\frac{2520{,}000000\times 981}{7{\cdot}8}}=2815$ vibrations per second. It will be observed that this frequency does **not depend** upon the **thickness** of the string: and hence if the three catgut strings of a violin be treated in this way they give out sounds of nearly the same pitch.

Glass or metal rods may be made to vibrate longitudinally in the same way: hold them by the centre and rub them lengthwise by a resined cloth; a shrill sound is produced.

If a violin-bow be drawn obliquely across a violin string, both transverse and longitudinal vibrations will be set up: a shrill squeak will then accompany the proper tone; whence the bow should always be drawn straight across the string, without any obliquity.

One source of Sound which is of considerable interest to the physician is the sound of **eddies** in Liquids flowing in tubes. Such eddies occur where the flow is in any way broken ; and they are most readily heard in **wide** tubes or with **high velocities** of flow. They are more readily formed when the **density** or the **viscosity** of the liquid is **small** ; and they may be favoured by **irregular constrictions** in the tube, or by the imperfect action of **valves.** In its relation to medical diagnosis the study of this subject is still incomplete.

Another is the deep-pitched boom of **contracting muscle**, which may be heard by means of a stethoscope placed over the muscle ; or by putting the fingers in the ears and forcibly contracting the jaw-muscles, with the teeth a little distance apart.

Another is the high-pitched sound of **stretched heart-valves** vibrating under the impact of an arrested blood-stream.

Harmonics.—In all the above cases of Vibration of bodies of regular form, we have confined ourselves to the **simplest** form of vibration which a body can present. But there is no case in which this form of vibration is the only one present. In the Vibration of a String, vibrating transversely, the motion will not be exactly the same as that of an ideal string executing one vibration only, and yet it may be practically **periodic**, that is, may repeat itself at regular intervals. If this be the case, the motion is made up of the **fundamental** or **slowest** vibration, together with others whose Frequencies are **twice**, **three** times, **four** times, etc., that of the fundamental or slowest vibration. (Compare Fig. 45.)

Thus the string in the problem on p. 202 will not only have a vibration whose frequency is 105·45 oscillations per second, but will also have others whose frequencies are 210·90, 316·35, 421·80, etc. per second.

In a **tinkling pianoforte** these "harmonic" vibrations, or components of the total vibration, are actually more powerful than the fundamental vibration or component; in a **violin** string, urged by a violin-bow, the 2nd, 3rd, 4th, 5th, and 6th are weak, while the higher components are ample, and render the sound penetrating; in a **banjo** or **guitar** the harmonics are very prominent; in a **pianoforte** string in good condition the lower harmonics up to the 6th are well marked, but those beyond are absent or feeble. The **amplitudes** of these harmonic components, relative to the fundamental vibration and to one another, depend upon the **mode** in which the string is **set in motion**—dragged out to an acute angle by a resined **violin-bow** and escaping from it when the tension becomes too great, **plucked** as in the banjo, guitar, harpsichord, **knocked** by a harder or softer hammer as in the pianoforte—and according to the **point** at which the Distorting Force is **applied**. The same considerations apply to **all forms of vibration**, whether transverse, longitudinal, or twisting, and whether the disturbances produced be compressional or distorting.

In most cases, however, the Total **vibration**, though **approximately** the same at each recurrence, is **not exactly periodic**; and the Total Vibration is made up of a fundamental vibration, together with others which only approximately correspond to true harmonics. This is what occurs in a string, for instance, by reason of its **stiffness**, that is, its want of ideally perfect flexibility; and in such bodies as stiff rods, or discs, or membranes, the higher-frequency components of the aggregate vibration are far from corresponding to any simple series of true Harmonics.

Forced Vibrations and Resonance.—Suppose we grasped the prongs of a tuning-fork, and pulled them apart, and let them go at regular intervals, the quasi-oscillations we produced would of course keep time with the Distorting Forces which we applied. This would not be a case of free oscillations of the tuning-fork, but a case of **forced oscillations**. The principle would be the same if our distorting force were applied very frequently: the result would be a Forced Vibration, which overpowered the natural tendency of the fork to free vibration at its own proper rate.

Two **clocks** on the same table will keep pace, for the impulses of their respective ticks, conveyed along the table, cause the one to hurry on and the other to slow down until the two clocks agree. The two prongs of a **tuning-fork**, even though not exactly equal in size, approach and recede from one another simultaneously.

The **more nearly** the Frequency of the applied intermittent Force agrees with the natural Period of Vibration of the body set in periodic movement, the **ampler** will be the oscillations produced.

If the externally applied Forces be so timed as **always to assist** and never to thwart the natural vibrations of the body set in vibration, the body may be set in ample Vibration by **very small forces**.

This may be illustrated by the ringing of a heavy bell with the aid of a **bell-rope**. The ringer does not try to pull the bell over at once: he gives a gentle tug to the rope, and then lets it go up: a feeble swing of the bell takes place, and the rope takes the bell-ringer's hands up: when the rope next slackens in his hands, he pulls it down tightly: and so for each occasion on which the rope tends to descend. He thus always helps it to descend, and never pulls against a tightening rope; and consequently the bell swings more and more widely, until at length it begins to ring. It is kept ringing by keeping up the same process of pulling regularly on a slackening rope. If the bell-ringer pulled against a tightening rope he would thwart the bell and check its movement.

If there be **two tuning-forks** of exactly the same frequency of natural or free vibration, and if we set both on the same table, the one of them being in vibration, the other fork will presently vibrate and produce Sound; the impulses of the one fork have disturbed the second at precisely the right intervals.

Even **across the air** of the room this effect will be produced: the small push upon the second tuning-fork, produced by any one compression of the air, is very small: but the compression is followed by a rarefaction, which releases the fork and allows it to swing back; the next compression comes in at the right time, and the fork is set more widely swinging. From small beginnings the vibration of the second tuning-fork is thus worked up, a little at a time, until at length it becomes considerable.

Generally, if any body capable of vibrating at a certain rate be exposed to impulses which recur at that particular rate, the body will begin to vibrate, and the Energy of the impulses will be absorbed by it. This phenomenon is known by the name of **Resonance**; and the body which is set in vibration is said to act as a **Resonator**.

If a body **vibrate** in such a way that it presents a Fundamental Vibration and a number of simultaneous Harmonic Vibrations, and if a tuning-fork corresponding to any of the **harmonics** be brought near, the tuning-fork will give out the tone of the component harmonic to which it corresponds. Such a tuning-fork, acting as a Resonator, will therefore serve as a means of **detecting** the presence of any particular **harmonic** vibration as a **component** in the Total Vibration of a sounding body.

Another form of Resonator serving the same purpose is a globe of glass or brass, of the form indicated in Fig. 125. If a Sound containing, either as a fundamental or as a harmonic tone, any tone corresponding to the natural period of free vibration of the air within the bulb A, be produced in the neighbourhood of the resonator, the listening ear placed at B will hear the air inside A loudly vibrating in unison with that tone; and a set of such resonators will enable the **different harmonics** of a Compound Vibration to be heard, and their relative intensities to be estimated.

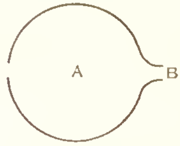


Fig. 125.

The principle of Resonance is applied in many **musical instruments**, particularly of the **wind** order. In a **reed organ-pipe** a vibrating reed produces a particular note; the air in the pipe resounds to it. In the **Clarinet**, the **Oboe**, the **Bassoon**, a reed of cane produces mixed vibrations when blown: the air in the pipe responds to one or other of these, according to the Length of the Resonating Column as determined by the particular keys pressed down by the player. In the **organ-pipe** a mixed set of vibrations is produced by a stream of air blown across the mouthpiece, and the air in the pipe resounds to that vibration which is in unison with its own natural period of free vibration. The column of air in the pipe has to be considered as if it were a **solid rod** of air bound at one end and free at the other; but not quite free. If it were quite free at its end the Frequency would be determined by the formula $n = 33200 \times \sqrt{\tau/273} \div 2l$, where l is the length of the column and τ the Absolute temperature; but it is not quite free; the vibrations are **hampered** by the task of lifting the external **atmosphere** at each oscillation; and so the vibrations are somewhat slower than this. The longitudinal movements of the air are greatest at the ends of the pipe; at the midpoint the air is nearly at rest, but is alternately squeezed together and relaxed. An organ-pipe blown too hard breaks into a sound an Octave above; that is, with twice as many vibrations per second.

If the upper end of an open organ-pipe be **stopped**, the column of air becomes like a rod clamped at one end, and the Frequency becomes **half** the frequency in the preceding case; that is, the sound produced becomes an **octave lower**.

If we change the gas in the pipe and use say **hydrogen** instead of air, the pitch is altered: with hydrogen the frequency is nearly four times as great: for hydrogen is a lighter gas than air, its density being only 0·07072 times that of air; and then, instead of the number 33200 (the velocity of sound in air, in cms.-per-sec.) we would have to use a number expressing the velocity of sound in hydrogen, namely, $33200 \div \sqrt{\cdot 07072} = 33200 \times 3\cdot 804 = 126,290$.

If the Atmospheric Pressure be increased, the pitch is **unaffected**. If the Temperature rise, the pitch rises, for the frequency is directly proportional to the *square root* of the Absolute Temperature.

The **Flute**, the **Flageolet**, the **Fife**, and the **Piccolo** resemble the Organ-pipe in principle. In **brass band** instruments the **lips** of the player are made to **vibrate**; the cavity of the instrument **resounds**, according to the size of that cavity, as determined by the construction of the instrument, or by the keys operated by the player, or, in instruments of the trombone class, by slides which lengthen or shorten the resonating cavity.

When a **shell** is placed near the **ear**, the warm-air currents in the shell produce a very slight sound, to particular components of which the shell acts as a Resonator, so that we then hear the well-known "murmur of the tide."

The **mouth-cavity** acts as a Resonator to the sounds produced by the larynx, as in the production of Vowels (p. 216).

Many **animals** have special resonance-cavities, such as a dilated hyoid bone, or their cheek-pouches, etc., which enable them to emit a very loud tone.

The passage from the exterior to the drum of the **ear** is apt to reinforce certain very high-pitched sounds, with disagreeable effect.

In many **stethoscopes** the upper part of the instrument is bell-shaped, and the **bell** acts as a Resonator for a particular sound. Sometimes there is at the top a resonating cavity whose size is **adjustable**, so that it may be made to resound to sounds of different pitches.

Many animals use their **ears** as reflectors of sound into the ear-passage; and there is in such a case a resonance-effect for particular sounds. The **hollowed hand**, applied behind the ear, acts in the same way.

When the **chest-walls** are set in irregular vibration by being **percussed** with the finger-tip, or with a rubber-capped hammer, or with a hammer tipped with a hollow rubber cap containing air, there is again a resonance-effect; not in every case produced by a **resonance-cavity** containing more or less air, as in the lungs, but sometimes by **semi-fluid** material, which is selectively set in resonance-vibration in a manner quite analogous to that in which cavities containing air act.

The **air in a tube** will sometimes **resound** to a **small flame** introduced into it. Take a lamp chimney, and let up into it a minute gas-flame from a blowpipe nozzle: in most cases the tube breaks out into a loud sound when the nozzle has reached a particular height. If it does not readily do so, the action may be started by singing or whistling to the tube a note a little higher in pitch than that corresponding to the natural period of vibration of the air within the tube. This note may be found by blowing across the end of the tube; the air in the tube will resound. The air in the tube vibrates forcibly when the "flame sings"; and the flame is raised and lowered during this vibration, so that its **image** if looked at in a **rotating mirror**, instead of being spread out into a plain band of light, appears spread out into a **band** of light with large **teeth**; or, in some instances, it may even be broken up into separate beads of light, as if to show that the flame had been extinguished at each vibration.

This device, a Rotating Mirror used along with a gas-flame, is frequently employed in acoustic experiments. A cavity is divided into two parts (Fig. 126) by a membrane, such as thin gold-beaters' skin. The one moiety of the cavity is connected with a conical mouthpiece A; the other is connected with a supply of coal-gas, which enters at B, and passes out at C on its way to be burned at the jet D. This contrivance is called **Koenig's Manometric Capsule.** When a sound is produced at the mouth of the cone A, sound-waves will impinge directly upon the thin membrane. These waves will cause motion of that membrane, which will pretty faithfully follow the variations of pressure due to the sound-waves. The **flame** will demonstrate this by its **variations in height.** If the flame be not looked at directly, but if its image be viewed in a rapidly rotating polished mirror, the image spreads out into a **band of light** serrated by large teeth, whose outline is itself serrated by smaller teeth. The **large teeth** correspond to the frequency and amplitude of the **slowest** or fundamental vibration, the **smaller** to the **harmonic** vibrations. For rough purposes the experiment may be carried out by prolonging the tube C into a flexible rubber tube terminated by a rat's tail jet, and **swinging the flame** in a circle before the eyes. The revolving mirror may then be dispensed with; and it is singular to note how the slightest change in the tone of the voice affects the shape of the serrations. It is often possible to find out by trial how to sing so as to keep the **larger serrations open** and free from subsidiary serrations: the tone of voice is then very **pure,** though it must be confessed it is somewhat hollow in quality. Instead of a cone we may use a **resonator** at A; the action of the resonator in response to an appropriate sound may then be rendered **visible** as well as audible.

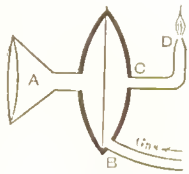


Fig. 126.

In the **sphygmophone** the supply of gas to a singing-flame is controlled by the pulse-beat; an audible effect is produced, keeping time with the pulsations.

The vibrations of the membrane in Fig. 126 follow the peculiarities of the sound-waves in the air: and these follow the peculiarities of the original vibrations of the sounding body. If a **writing-point** were attached to the membrane, it could make a mark upon a rotating smoked-glass drum; this mark would be a straight line so long as the membrane was at rest, but would present little tremors when a sound was being produced outside the cone A; and this was accomplished in instruments called **phonautographs.** In Edison's **phonograph** an advance was made; the writing-point was made to drive its way more or less deeply into the substance of a strip of tinfoil on a rotating drum; this tinfoil thereafter bore on its surface a **groove** of varying depth; and if at any time thereafter the same writing-point were made to travel in the same groove by rotation of the tinfoil under it, the whole process was **reversed**. The groove then actuated the Writing-point, the writing-point the Membrane; the membrane acted upon the Air, subjecting it to compressions and rarefactions resembling the original; Sound-waves were thus set up, again resembling the original; and these, when they reached the listening Ear, produced a sensation of Sound resembling the original sound. In the newer forms of the phonograph the groove is not pressed in tinfoil, but is cut out of a cylinder or disc of wax, and a different point is used for reproducing from that which is used for cutting the groove in the wax.

The Vibrations of a Membrane do **not perfectly** follow the variations of Air-Pressure which give rise to them; and hence the reproduction of Sound by the Phonograph is not entirely faultless. It often happens that the **higher components** are exaggerated; and this results in a more or less nasal quality of tone.

The Human Ear.—If we have a **series of Resonators** of any kind we may **analyse** any Sound-waves so as to find their Component Vibrations. Each resonator will resound to its own component; and a sufficiently extensive series of resonators will enable us to trace out all the components. If we can imagine such a series of Resonators, **each with its own observer**, we would have, in principle, a picture of what, according to Von Helmholtz's theory, takes place in the **Human Ear**. According to this theory, the human ear is, in effect, an enormous battery of some thousands of **resonators**, each with its appropriate **nerve-end** which, through the corresponding **nerve-fibre**, reports the action of the corresponding resonator to the **brain**. The **component** Vibrations of the most complex Sound-waves are thus reported **separately**; and the Brain **blends** the individual reports into that **summary** which we call the **Sensation of Hearing**.

There are serious difficulties, anatomical, experimental, and pathological, in accepting Von Helmholtz's theory as it stands:

but the student will do well to understand that theory in the first place, as a basis for his further study.

The order of events is, according to this theory :—

(1) The vibrations of the air are communicated to a membrane, the **drum of the ear**. The Amplitude is much decreased, and the Force correspondingly increased.

(2) The vibrations are transmitted from the drum of the ear through a **jointed chain** of osseous **levers**, the last arm of which moves less than the drum of the ear itself, with corresponding increase of Force : and are taken up by a **second membrane**.

(3) This membrane communicates them to a quantity of **liquid** in a **closed sac**, partly bounded by this membrane.

(4) They are transmitted through this liquid to a **triangular** membrane, the "**basilar membrane**," **stretched transversely** and in contact with liquid on both sides. Of its own accord this membrane could, being hampered by the liquid, only oscillate much more slowly than it would in free air. It enters into vibration by Resonance, not as a whole, but only in **localised transverse strips**, whose proper rates of vibration correspond to the various components of the mixed vibration communicated to the membrane as a whole.

(5) Each localised vibration of the membrane affects a **local nerve-end** apparatus, of which there are 16,000 to 20,000.

(6) Each nerve-end apparatus is continuous with a **separate nerve-fibre**.

(7) The 16,000 to 20,000 fibres converge and form the "**auditory nerve**," which, by its separate fibres, conveys the separate local impressions to the **brain**.

(8) The **brain** blends these impressions.

What the Ear, taken as a whole, thus perceives is the **impact** of **sound-waves** : and as these differ in their Frequency, their Amplitude and their Complexity, so do the Sounds heard differ in their **pitch**, their **loudness**, and their Quality or **character**.

Pitch.—The greater the Frequency, the higher the Pitch.

Take a long strip of iron say 4 feet in length : fix it in a vice : pull it aside and let it go : it will oscillate transversely at a rate such that the oscillations can be counted : remove it and refix it so that only 2 feet of it are now free to move : it will now oscillate four times as frequently : 1 foot, 16 times : 6 inches, 64 times as frequently as at first ; and so on. When the oscillations become sufficiently frequent, we hear a **sound**: and as the free vibrating part of the strip is **shortened**, the **pitch rises**.

The Pitch depends on the **Frequency** of the **Fundamental Vibration** of a sounding body: for it is to this alone that our ears are accustomed to listen.

We may specify the Pitch of a sound by stating the Frequency of its fundamental vibration, or else by stating its place in the conventional **musical scale.** In the Musical Scale the starting-point is the *a* tuning-fork of 435 vibrations per second. Then the corresponding notation, for the scale of pitch represented by the white keys of a pianoforte, is the following:—

c'	d'	e'	f'	g'	a'	b'	c''

261	293·625	326·25	348	391·5	435	489·375	522
1 :	$\frac{9}{8}$:	$\frac{5}{4}$:	$\frac{4}{3}$:	$\frac{3}{2}$:	$\frac{5}{3}$:	$\frac{15}{8}$:	2

Sounds whose frequencies bear the ratios indicated by the last preceding line form a series which is found to satisfy our ears and to be suitable for the purposes of musical art. It will be noted that c'' has twice as many vibrations per second as c'; the interval between them is an **octave.** Between c' and g', or e' and b', or f' and c'', the ratio is 2 : 3; and in each of these cases the interval is a **fifth.** Between c' and f', or d' and g', or e' and a', or g' and c'', the ratio is 3 : 4; and in each of these cases the interval is a **fourth. Equal intervals** between two pairs of musical notes thus indicate **equality of ratios** between the Fundamental Vibrations of each pair.

The series of notes above given is repeated above and below the particular octave specified: but the difference between the notes of one octave and those of the similar octave below it is, that the Frequencies of the notes in any octave are **twice** those of the corresponding notes in the **octave** immediately **below.** For example, following up the octave given, we have c'', d'', e'', f'', g'', a'', b'', c'', with frequencies 522, 587·25, 652·5, 696, 783, 870, 978·75 and 1044 per second; numbers which are **twice** those pertaining to the octave given above, but which present the **same ratios**, and a corresponding **equality** in the musical **intervals**.

The sounds which the Human Ear can perceive range from about 16 to perhaps 40000 fundamental vibrations per second: but there is a great difference in this respect between different persons. Cats can hear a whistle which is too high-pitched for a man to hear.

The deep-pitched boom of contracting muscle corresponds to about 19 or 20 impulses per second.

The **Loudness** of a Sound tends to be proportional to the **energy** of the Vibration and therefore to the *square* of the **amplitude** of vibration of the sounding body: but where we have to do with sounds of different pitch we find that the **apparent loudness** also depends upon the **sensitiveness** of the **ear**. And further, in the open air the amount of Energy transmitted to the ear, and therefore the corresponding Loudness of the Sound perceived, varies *inversely* as the *square* of the **distance** of the sounding object. If, however, we do not allow the sound-waves to broaden out in the open air, but **confine** them within **tubes**, the sound may be carried to a great distance, as along sewers, speaking-tubes, etc., without great loss of loudness; and if we **concentrate** the waves—as by **hearing trumpets** or as in **phonograph** ear-pieces, or in those **stethoscopes** in which a conical tube terminates in a narrow tube fitted into the ear, or in two tubes fitted into both ears—we may render sounds distinctly audible which without this it might be difficult to perceive.

Quality, Character, Timbre.—The **degree of complexity** of a Sound (the number of Harmonics present), together with the **relative** prominence or **loudness** of **each** Harmonic, as reported to the brain by the mechanism of the internal ear, is interpreted mentally as giving a distinctive Quality or Timbre or Character to the sound heard. We hear a **violin** sounding a note, say a'; we can not only identify the pitch of the note, but we can say that it is produced by a violin, and by a good or bad violin, or by a good or bad player. We do **not consciously** hear the **harmonics**, as a rule; we **hear the note** a', of a certain quality, quite distinguishable from the note a' produced by a human voice or by a pianoforte string. When a sound is almost free from harmonics we have, in the higher notes, a flute-like quality; and we have already explained how the vibrations of a violin string differ from those of a pianoforte string or of a banjo string. If we have at command a number of flutes which produce notes whose Frequencies are in the ratios 1 : 2 : 3 : 4 : 5, etc., and have our apparatus so arranged that we can cause these to sound with loudnesses which we can separately regulate at will, we can **build up any quality** of Sound; and thus the infinite variety of qualities of sound which we hear in Nature is very simply explained. Even the different **vowel-sounds** themselves depend on nothing other than this: a sound produced by the larynx, and given a particular Character or Quality by **resonance** on the part of the mouth-cavity held in a particular way, is recognised by us, in virtue of that **Character** or **Quality**, and of nothing else, as a Vowel-sound.

If we shape our mouth as if for a particular vowel, and sound a Jew's harp near the lips, the vowel-sound is heard.

If we listen to a **tuning fork** in the open air, it seems to say *ōō*; if we press its shank against a **table**, it seems to say *ō*, for the table emits the octave as well as the fundamental tone, on account of a certain pressure exerted on the table by the fork at the end of each **half-oscillation**.

The **sounds** which we hear in Nature vary very much in their complexity. They range from pure Tones, through tones with Harmonics, and tones, still musical, with harmonic vibrations not well in tune with the fundamental; but they are all more or less regular, with more or less well-defined Pitch.

Noises, on the other hand, are due to an admixture of sounds whose Frequencies bear **no relation** to one another; for example, the mixture of sounds which make up the hum of a town. If sounds of a low pitch predominate in the mixture, the general effect is that of a low-pitched roar or hum; if sounds of a high pitch, the result is a high-pitched hiss or whistling.

Discord.—Where two musical sounds are simultaneously heard which differ by say 32 vibrations per second, there will be 32 **beats** per second between the Fundamental Tones, and this is disagreeable to the ear, as **flickering** is to the eye. Further, if two notes are simultaneously sounded which are too near to one another, the part of the Basilar Membrane which lies between the regions properly set in vibration is also disturbed, and there is **difficulty in identifying** the **pitch**; and this again is painful. Two notes may thus produce a painful impression when sounded together, and are then said to **discord** with one another. The **harmonics** of these notes may also produce disagreeable Beats against one another, and thus give rise to Discord. The combination of notes which produces this effect to the least extent is the **common chord**, a Note, its Major Third, its Fifth, and its Octave, with the ratios $1 : \frac{4}{3} : \frac{3}{2} : 2$; for in such a combination the Harmonics mostly coincide, and the Difference and Summation Tones, of which presently, belong to the chord itself. The Common Chord is therefore the most pleasing or harmonious combination of four notes within the octave.

Difference and Summation Tones.—The **drum of the ear** moves **more readily inwards** than outwards; and Von Helmholtz showed that in any transmitter presenting this peculiarity, when the original sounds produced were two, of frequencies n and n', the sound transmitted corresponded to four, of frequencies n, n', $n+n'$, and $n-n'$. Again, it is assumed in the elementary theory that the Displacement of the air produced by the two sounds acting together is the **sum of the displacements** produced by them severally; but this is **not quite** the case: this sum is not quite attained: and that is equivalent to the addition of a **new vibration**, whose frequency is $n-n'$. These conclusions are confirmed by experience. When two sounds of Frequencies say 200 and 300 are sounded together there are heard, faintly, a deep **differential tone** of 100 ($=300-200$), and a shrill **summational tone** of 500 ($=300+200$) vibrations per second. These differential and summational tones are thus mainly subjective in their origin, and are not due to Beats, with which they may co-exist.

The **energy** of sound-waves is derived from the **energy of vibration** of the vibrating bodies; the production of Sound-waves robs these bodies of Energy, and these vibrating bodies **come to rest** unless Energy be continuously supplied to them; and the Energy which has been given over to the air or other medium is ultimately **reduced** to the form of **Heat**, while at the same time the air or other medium itself tends as a whole to reassume its original comparatively undisturbed condition.

CHAPTER VI

HEAT

We have incidentally found, in dealing with the Properties of Matter, that these properties are affected in various ways by the *temperature* to which a substance is brought: and thus we have already considered the way in which a change in the temperature of a gas affects its volume (p. 76), that in which a change in the temperature of a liquid affects its volume (p. 113), its surface-tension (p. 117), the solubility of gases in it (p. 119), its rate of diffusion (p. 121), its osmosis and osmotic pressure (p. 123), its evaporation (p. 127), and its viscosity (p. 158); as also the way in which a change in the temperature of a solid affects its linear dimensions and its volume (pp. 172 and 174); and the effect of temperature upon the pitch of Sound produced by the vibration of a gas (p. 197).

We have also, by this time, become familiar with the idea that the **Heat** of a body is the **Energy of Translation, Spin** and **Vibration** of the several **Molecules** of the body; and therefore we may say that **Heat is a form of Energy.** Let us note, however, before proceeding farther, that the name Heat is also applied to a **wave-motion** in the Ether, which wave-motion is induced by the Vibrations of the Molecules of a hot body; and the Energy of this wave-motion is called **Radiant Heat.** Of this we shall have something to say later. To distinguish the ordinary Heat of a hot body from this

Radiant Heat, it is sometimes called **Sensible Heat**; but more generally it is simply called **Heat**.

We become aware of the Heat of a hot body, in the first place, through our **cutaneous sense** of heat. We feel the same body, at different times, to be warmer or colder: and our cutaneous sense of heat (which is quite distinct from that of touch and is apparently due to a different set of cutaneous nerve-ends and nerve-fibres), reveals to us the presence of a more or less heated condition in the body; for the **molecular agitation** of a heated body affects the appropriate **nerve-ends** in the skin.

A cave or large building, which retains much the same temperature throughout the year, seems cool in summer and warm in winter.

In the earlier years of science, it was supposed that **Heat** was an invisible **substance** without Weight, called **Caloric**; but no one now entertains this idea.

The **Energy of Work** can be **transformed into Heat**. When we rub a **lucifer match** on its box we do Work: the Energy of this work is converted into Heat; the match-head becomes heated, and ignites. When the **brake** of a vehicle or railway train is put on, the Kinetic Energy of motion, which disappears, is transformed into Heat in the brake. When **metal** is **filed** or bored or turned, Heat is developed at the expense of the work done. When a **bullet** is stopped by its target, it becomes hot and may even fuse; the Kinetic Energy of the flying bullet is transformed into Heat. When a **liquid** is made to flow in **pipes**, the Energy which is expended in keeping it in motion is ultimately transformed into Heat.

Mr. Joule measured the quantity of Heat evolved by doing Work upon a given quantity of **water**. He expended work to a known extent in churning water in a vessel, by means of a paddle rotating in the water; and he found that if he expended 772·55 foot-pounds of work upon 1 lb. of water, he raised the Temperature of the water from 60° to 61° F. This is as much as to say that

41,593000 ergs of Energy, in the form of Heat, raise the Temperature of one gramme of water through 1° C. Subsequent investigations have shown that this figure is somewhat too low; and we shall say that the **amount of heat** required to raise the **temperature** of **one gramme of water** by **1° C.** is **41,750000 ergs.**

Heat, being a form of Energy, can be measured in ergs (or in foot-pounds); and the Unit of Heat on the C.G.S. system would be one Erg. But this is not a very convenient unit, being far too small: and we have to consider five different units which are in practical current use.

(1) The **small calorie** (abbreviated to *ca*): the amount of heat required to raise the temperature of one **gramme** of water from 0° to 1° on the Centigrade thermometer: the C.G.S. unit; 41,750000 ergs, as above.

(2) The **large calorie** or kilogramme-calorie (*Ca* or *kgr.-ca*): the amount of Heat required to raise the temperature of one **kilogramme** of water through 1° C.; the Continental engineer's unit; 41750,000000 ergs.

(3) The **British unit of heat**: the amount required to raise the temperature of 1 lb. of water through 1° Fahrenheit; 11690,000000 ergs.

(4) The **Pound - Centigrade unit**: the amount required to raise the temperature of 1 lb. of water through 1° Centigrade; 21042,000000 ergs.

(5) The **Joule**: 10,000000 ergs; the "Practical Electromagnetic" unit of heat: the amount of Heat developed during each second in an electric conductor whose resistance is one Ohm, when a current passes in it whose strength is one Ampere.

Whenever Energy is **liberated** in a substance **in** a way which does not guide it in any particular **direction** or make it assume any specialised **form**, that Energy appears in the form of **Heat.** Let us, for instance, burn a bit of **charcoal**; before combustion the Charcoal and the Oxygen of the air had some **potential energy** of separation and **mutual chemical attraction**, and upon combining they lose this. But this Potential Energy must assume some other form. If the charcoal be burned in the open air, some of the Energy is expended in setting up Waves in the Ether, as **Light** and **Radiant Heat**. The remainder of the Energy liberated is not guided by the environment into any specialised form, and appears as **Heat**, so that the carbonic acid produced by the process of combustion is itself hot.

If, however, we conduct the combustion within a closed opaque vessel; if, for example, we burn the charcoal within a closed metal vessel filled with oxygen, which we may surround with water; then we find that there is no Light visible and no direct Radiation of Heat; that is to say, there is no loss of Energy by transmission thereof through the Ether; and in that case all the Energy liberated on combustion is confined to the metal casing and the surrounding water. We may measure the rise in the Temperature of the surrounding water, and thus find how many units of Heat have been liberated during the process of combustion: for example, one gramme of pure carbon liberates 8080 *ca* or 337340,000000 ergs. An apparatus of this kind is called a combustion-bomb, or a **combustion-calorimeter** or measurer of the Heat developed during Combustion.

Fig. 127.

The combustion-calorimeter just described is a particular example of **calorimeters** or **heat-measurers** in general. When we want to know the **amount of Heat liberated** (as distinguished from the **temperature attained**), we may surround the source of heat by water and ascertain the **rise of temperature** in the known quantity of water: and this, at one calorie per gramme of water per degree Centigrade, gives the **number of calories** of Heat evolved. We shall see afterwards how to allow for the vessel containing the water, which itself takes up some of the Heat evolved.

The amount of Heat liberated on the Combustion of 1 gramme of pure carbon, 8080 *ca*, is the "**combustion-equivalent**" of pure carbon. Different substances have different Combustion-

Equivalents. For example, a gramme of carbonic oxide, on combustion, liberates heat to the amount of 2403 *ca*.

This example, of carbon and carbonic oxide, is instructive. Our one gramme of **carbon** yields 8080 *ca* of heat on complete combustion to carbonic acid (CO_2), whose amount is $3\frac{2}{3}$ grammes: the amount of **carbonic oxide** which will yield the same amount of carbonic acid is $2\frac{1}{3}$ grammes; these $2\frac{1}{3}$ grammes will yield on combustion, at 2403 *ca* per gramme, 5607 *ca*. The **combustion** of **carbon** into carbonic acid may thus be divided into **two stages**; first the combustion of carbon into **carbonic oxide**, which liberates 2473 *ca* per gramme of carbon; and secondly, the combustion of the corresponding carbonic oxide into **carbonic acid**, which liberates 5607 *ca*. The first stage of the combustion thus liberates a good deal less Energy than the second: and this is accounted for by the circumstance that in the first stage the carbon is reduced from the Solid to a Gaseous condition, a **change of state** which absorbs Energy.

If we take a certain volume of mixed **hydrogen** (2 vols.) and **oxygen** (1 vol.) and explode the mixture by an electric spark, so that water-vapour (H_2O) is produced, we may distinguish **three stages** in the condensation of the products, each with its own corresponding evolution of Energy. First, we may take the stage at which the **water-vapour** occupies the **same volume** as the original gaseous mixture; at this stage the temperature is 136°·5 C., and the Heat liberated is 28580 *ca* per gramme of hydrogen. Second, let the **water-vapour** cool down to **100° C.**; it then comes to occupy two-thirds of the original volume, and during this shrinkage more heat is liberated, so that the total Heat liberated is 28738 *ca* per gramme of hydrogen burned. Third, let the products condense to liquid **water** and cool down to **0° C.**; then this change of state results in the liberation of still more heat, so that the total Heat liberated is 34462 *ca* per gramme of hydrogen burned.

A gramme of urea when burned liberates 2206 *ca*; one of starch 3901 *ca*; one of dry albumen 4998 *ca*; and one of fat 9096. **Hydrocarbons**, such as heavy paraffin oil, have, weight for weight, a higher combustion-equivalent than pure carbon, and still more have they a higher combustion-equivalent than ordinary coal: so that the heating value of paraffin oil, or the amount of water which can be boiled by means of a given amount of it, is greater than that of ordinary coal.

Change of State

Every **change of state or condition** is, as a rule, associated with the **evolution** or the **absorption** of Heat; and it may be necessary to supply or to take away heat before the Change of State can occur. Of this there are numerous examples.

If a **gas** be heated, it expands if it can, but remains a Gas. If it be cooled down, it shrinks in volume if it can: and when it is below its Critical Temperature, it will condense into a Liquid if the pressure be sufficient. **Liquefaction** of a **gas** is thus associated with **loss of Heat**, and loss of Heat with a tendency to liquefaction. Conversely, **evaporation** or volatilisation of a liquid is associated with **absorption of Heat**; and absorption of Heat by a liquid is associated with a tendency to volatilisation.

If a **liquid** be **heated** it generally evaporates or volatilises unless it is decomposed by the heat; if it be **cooled** sufficiently it generally solidifies.

If a **solid** be **cooled**, it simply becomes cold, without change of state; if it be **heated**, if it be not decomposed it is **liquefied** or **fused**, if the rise of temperature be sufficient. In many cases the Temperature applied, in order to melt or liquefy the solid, must be extremely great, that of an electric arc for example; in others the temperature at which Fusion takes place is considerably lower, and in still others we ordinarily see bodies at temperatures above that of their **melting** or **fusing point**.

Metallic mercury melts at $-40°$ C.: hence we usually see it melted or liquid, not solid. Platinum, on the other hand, does not melt below 1775° C. Alumina is infusible in all ordinary furnaces, but can be melted in the electric arc.

In most cases of Fusion by heat, some **energy** has to be **absorbed** in order to do the **work** of tearing the Solid up into a Liquid.

For example, when ice is melted, a considerable amount of heat (80·025 *ca* per gramme) is absorbed by the ice during the process of melting. This produces no effect whatsoever upon the Temperature: and thus if we communicate to a **gramme of ice** at 0° C. 80·025 *ca* of Heat, the result is one **gramme of water**, still at 0° C. The 80·025 *ca* of Heat thus seem to have disappeared, and as sensible heat they have disappeared; and the **Energy** in the form of Heat, which thus seems to disappear, was called in the days of the material theory of heat, and is still called, the **Latent Heat of Water**. The 80·025 *ca* have not been destroyed; as Energy they remain, and will be restored as Heat by the water upon its freezing or solidifying into ice. Suppose we have a gramme of water at 0° C., and that we expose it to a still lower temperature, so that it loses Heat to surrounding bodies: as it goes on losing Heat, more and more of the water assumes the **solid** form: this goes on until 80·025 *ca* of Heat-Energy have been lost by the gramme of freezing water; not until all this Energy has been lost will the whole of the water be converted into ice; and not until this has occurred will the Temperature fall in the least degree below 0° C. Thus the production of ice is not instantaneous, but goes on *pari passu* with the loss of the so-called Latent Heat by the freezing water.

In an **ice-calorimeter**, the amount of ice is measured which can be melted by means of Heat evolved within a chamber surrounded by ice: the number of grammes melted, at 80·025 *ca* per gramme, gives the number of calories of Heat evolved.

How much ice will be required to cool 1 litre of water at 15° C. to 5° C.? One litre = 1000 grammes; this quantity of water must be deprived of $1000 \times 10 = 10,000$ calories of Heat. Each gramme of ice will take 80·025 *ca* to melt it and 5 *ca* more to raise it to 5° C.; or 85·025 *ca* in all. The number of grammes of ice required is therefore $10,000 \div 85{\cdot}025$ or 117·6 grammes.

A **hot-water bottle** contains a considerable number of calories of Heat, according to its size and its temperature; and these can be liberated at any desired point. Better than a hot-water bottle is a bottle filled with **fused** crystalline **acetate of soda** ($CH_3CO_2Na,3H_2O$). When this substance is cool it is solid; but if the bottle or tin case containing it be immersed in boiling water, the salt first melts and then reaches a temperature of 100° C. When allowed to cool, it first cools down to 58°·5 C., and then remains at that temperature, continuously giving off its **latent heat of liquefaction**, until the whole of the salt has assumed the solid form. Thereafter it cools down just as an ordinary hot-water bottle would do.

In some cases the substance, while undergoing a **change of state** or of condition, withdraws Energy from **its own molecules**, which thereupon become **cooled**.

When a Gas is suddenly compressed, Work is done upon it; this work appears as Heat in the gas, and the gas becomes hot. If the compressed gas be allowed to return immediately to its original Pressure and Volume, it regains its original comparatively cooler Temperature. If, however, it be allowed, while compressed, to cool down to the temperature of the surrounding air, it will, on being allowed to expand, become very **cold**. While expanding, it does exterior **work** against the Atmospheric Pressure; and the Energy requisite to enable the gas to do this exterior work it has obtained by robbing its own molecules of part of their energy, that is, of part of their Heat. The gas as a whole therefore becomes colder.

A jet of **high-pressure steam**, when liberated into the air, suddenly expands; it thereupon becomes colder, and partly condenses into scalding droplets of hot water. A little farther on, by reason of Friction, the jet loses velocity and momentum; its Energy of flow is converted into Heat; and the droplets evaporate, so that the steam becomes transparent and dry. When the steam is in this condition, it may even cause evaporation of moisture from any moist surface on which it plays. Farther on, it cools down and forms droplets of hot water: it is now again opaque and scalding. It then cools down into the ordinary "cloud of steam" which we see left by a railway locomotive engine.

Where **evaporation** of a Liquid takes place without a corresponding amount of Heat being supplied, again the remaining molecules are robbed of part of their Energy, and there is **cooling**.

As examples of Cooling due to Evaporation we may take the cooling of the **skin** by perspiration or by a draught of air or by wetting it and allowing it to dry; a dog cooling himself by panting with his **tongue** exposed: the cooling of water by a **porous water-cooler**, the water in which partly oozes to the surface and there evaporates: cooling a room by throwing water on the floor: cooling of air in coal-pits by blowing water-spray into it: cooling of compressed air in refrigerators and compressed-air mechanism, by the same means: cooling of a liquid which is being rapidly evaporated, as in the ammonia process of ice-making, where liquefied ammonia is made to evaporate very rapidly under an air-pump and becomes extremely cold: and the evaporation of liquid carbonic acid, which may become so cold that it assumes the solid form. Liquefied air, when allowed to evaporate freely, assumes temperatures below – 210° C.

Chloride of ethyl boils at 35° C., a temperature lower than that of the body (36·9 C.): hence this liquid will boil, or at any rate emit vapour rapidly, if a bottle containing it be held in the hand. If a little bottle of this liquid, with a fine nozzle-jet, be inverted and held in the hand, the rapid evaporation forces liquid out through the nozzle: the jet of liquid will rapidly cool any surface on which it impinges; and if the evaporation be accelerated by directing a blast of air on the same spot as the chloride-of-ethyl jet, complete local anæsthesia, or numbness to sensation, may be set up within a few seconds.

When a liquid has its temperature raised sufficiently to enable it to boil, the process of Boiling is rendered much more regular by putting something with a rough surface into the liquid. Bubbles are then formed at the sharp angles of the substance so employed, say platinum foil: and molecules escape into these bubbles, which thus expand and rise. If this be not done, and particularly if the flask or other vessel be of glass, the whole liquid may become heated to a temperature above that of the vapour formed, and it may give way explosively, forming a tumultuous rush of vapour, while the temperature falls back even below the normal boiling-point; and thus the liquid may "bump" and may even break the flask. At each bump, the momentary fall in temperature is due to the rapid transformation of liquid into vapour.

Where liquefaction of a solid takes place without a corresponding amount of Heat being supplied, the Energy required to do the internal work of pulling the molecules loose is obtained at the expense of the Heat-Energy of the molecules themselves; the liquefied material is accordingly cold.

If we put a quantity of "hyposulphite" of soda into water, the temperature falls very greatly as the salt dissolves. This is the principle of "**freezing mixtures**," in which very soluble salts, such as nitrate of ammonia, are dissolved in cold water; the mixture becomes extremely cold. Solid carbonic acid, dissolved in ether ($C_4H_{10}O$), falls to a temperature of $-100°$ C.

Fahrenheit intended the zero of his thermometer to represent the temperature attained by a liquefied mixture of snow and salt. When the pavements are cleared by means of salt in winter weather, the brine which is produced is at first at a temperature of about 0° F., or "thirty-two degrees of frost": and it therefore chills the feet of pedestrians, while it refuses to dry, because it absorbs moisture. Salt should never be used for any such purpose, except in cases where its application is to be immediately followed up by that of the brush to sweep the pavement clean.

If, on the other hand, there be Chemical Combination between the solvent water and the salt dissolved, or a break-up of the molecules of the salt, with evolution of Energy, the Energy thus evolved may suffice, or even more than suffice, to supply the energy required and absorbed in the proeess of Liquefaction. For example, if **carbonate of potash** be dissolved in water, the chemical combination between the carbonate and the water, in which hydrates of the salt are probably formed, results in the liberation of a large amount of Energy; the consequence is that the solution becomes **very warm**; the cooling due to liquefaction of the salt is considerably more than overpowered by the heating due to the chemical combination between the carbonate and the water.

When a Gas or Vapour becomes a Liquid, there is generally an evolution of Heat.

When steam at 100° C. condenses to water at 100° C., 546 *ca* of Heat are evolved per gramme of steam condensed. This is applied in low-pressure **steam-heating** of buildings; and in steam-heating in chemical operations, in which the steam is led through a worm or spiral metal tube which traverses the liquid to be heated. The Heat so liberated is called the **latent heat of steam**; and in order to convert a gramme of water at 100° C. into steam at 100° C., 536 *ca* of Heat must be supplied to it.

When **rain** is formed by the condensation of moisture in the air, the change of state from the vaporous to the liquid condition results in the liberation of Heat, which is lost by the water-vapour and taken up by the surrounding air. The fall of rain thus exercises a mollifying effect upon the climate.

When a Liquid becomes a Solid, there is generally an evolution of Heat.

For example, if we set aside a strong solution of sulphate of soda in hot water, and keep it at perfect rest, it may remain liquid without depositing crystals, though it becomes cool; it is then a **supersaturated solution**: but if we drop in a crystal of sulphate of soda, the whole solution becomes a **solid** mass of crystals, and at the same time becomes **very warm.** When water is dropped upon unslaked **quicklime**, the lime becomes very hot, partly on account of the chemical combination between the lime and the water to form hydrate of lime, and partly on account of the water assuming the solid form.

In all cases of **evaporation** or **boiling**, the substance whose state is being changed comes to occupy an **increased** bulk or **volume.** In addition to the Energy which has to be supplied in order to effect the **change of state**, we have therefore to supply Energy in order to do the **work** of **raising the atmosphere**. If evaporation take place without Heat being supplied from without, there will be a still further amount of cooling due to this cause.

In change of state from the Solid to the Liquid form, or *vice versâ*, we seldom have occasion to concern ourselves much with the Work done by or against Exterior Pressures. But these are not wholly to be neglected; and one consequence of the action of atmospheric or other exterior pressure is, that the **greater** the exterior **pressure** the **lower** the **melting point** of **ice**, by ·0074° C. per atmosphere pressure.

When ice melts it contracts; when it thus contracts, exterior work is done by the exterior pressure; and when the exterior pressure is increased, the ice yields more readily into the melted state.

This lowering of the melting point of ice by increased external pressure has some important consequences. If two pieces of ice, not very much below 0° C., be **pressed** together, the ice will **melt** at the points of contact; and when the pressure is relieved, the melted ice again **freezes** and the lumps of ice **cohere.** If a block of ice have heavy weights hung upon it by a wire which is passed over the block, that wire will **cut** its way **through** the block, but the ice will **close up** behind the wire, so that the wire appears to traverse the block without cutting it. When **crushed** ice is pressed through a narrow passage, the lumps of ice melt, cohere, are crushed, recohere, and so on, until the whole mass **flows**, very much as if it were a Viscous Fluid : a circumstance which has been called in to help in explaining the flow of **glaciers**.

Ice is one of the very few substances in which the melting point is lowered by pressure. In by far the most part of all fusible substances the melting point is, like the boiling point, raised by pressure, and the liquid formed by fusion is more bulky and lighter than the solid, so that the solid sinks in the melted liquid.

If we **dissolve** any soluble substance in a liquid, say sugar in water, the **freezing point** of the liquid is **lowered**.

The lowering of the freezing point does not depend on the nature of the substance dissolved, but only on the **number of molecules** added to the solvent liquid, and on the nature of the **solvent liquid** itself. For every one molecule of any substance dissolved in 10,000 molecules of water, the freezing point is lowered 0·0063° C. Salts when they dissolve in water generally break up more or less completely into **ions** (p. 123), and thus increase the total number of molecules. Sometimes, on the other hand, there is polymerisation or **coalescence** of molecules upon solution, so that the freezing-point is not lowered so much as the above rule would indicate.

Sometimes Solids become Gases or Vapours directly, without passing through the Liquid state.

Thus **cold high winds** will remove **snow** from the surface of a country without melting it, by a process of true evaporation. **Arsenious acid** and a few other substances evaporate in this way when heated ; and their vapour condenses directly into the crystalline form. Such substances are said to "**sublime**" upon heating : but the term is also applied to cases such as those of sulphur and benzoic acid, in which the substance heated does melt before evaporating, though the vapours are condensed at once into the solid form without depositing in the first place as a liquid.

The **rate** at which a given chemical or physical Change of State or condition is effected is of **no consequence** whatever in determining the **amount of Heat** which will be liberated or absorbed.

If we submit starch to direct **combustion** it will, on complete oxidation, evolve a certain amount of heat, 3900 *ca* per gramme. If we expose it to **putrefactive processes** or to **slow oxidation** in the body of an animal, so that it is ultimately oxidised into carbonic anhydride and water in the same ultimate condition, it will evolve in the long run **precisely the same** amount of Heat, however long a time may be taken in reaching this result. There will be no such high Temperatures attained in the slow process, because the Heat, as it is gradually liberated, is continuously dissipated by conduction or radiation; but if this dissipation of Heat be checked, relatively high temperatures may be attained, as in the heating, charring, and ignition of masses of **damp hay** while undergoing too rapid a fermentation. A **candle** burns away more rapidly in compressed than in ordinary air; but the amount of Heat evolved by it remains precisely the same.

Beef or mutton fat has a heating value of about 9000 *ca* per gramme, meat free from fat one of about 5200. The **combustion-equivalent** of the **whole diet**, *less* that of the **excreted** urea, etc., gives the amount of **energy** which has to be accounted for in the **human body**: and this Energy is accounted for as **mechanical work done** (about 15 per cent of the whole) and **heat produced** (about 85 per cent). The **muscles** are the principal thermogenic tissues; and the **glands** of the body also liberate much heat when in action, through the chemical changes going on within them. In the process of **digestion**, heat is absorbed during the reduction of solid food to a fluid state, or liberated by the processes of hydratation or dehydratation, or by synthesis of such things as hæmoglobin or blood-plasma. In **fevers** the nitrogenous compounds of the body are being oxidised, and the evolution of Heat is greater than radiation, evaporation by the lungs and skin, etc. can carry away. On exposure to moderate cold, the nervous system stimulates the system to increased activity, and Heat is more rapidly generated.

If we have a **number of changes of state** or condition going on at the **same time**, we have to make up an account of the evolutions and absorptions respectively due to each.

The combustion of one gramme of ordinary hydrogen with eight grammes of ordinary oxygen, to form water at 0° C., yields 34,462 *ca* of heat; but the same quantities of nascent hydrogen and nascent oxygen yield 54,623 *ca*. This shows that the true phenomenon is, an **absorption** of 20,161 *ca* in breaking up the hydrogen and oxygen into atoms, and a simultaneous liberation of 54,623 on the combination of these atoms to form water: the balance of the account showing a liberation of 34,462 *ca.*

Most chemical compounds give out *less* Heat when completely burned than their component elements do. For example, acetic acid liberates, upon complete combustion into carbonic acid (CO_2) and water-vapour, less heat than its carbon and hydrogen would do when supplied with an adequate amount of oxygen and burned. The acetic acid is as it were already partly oxidised, and complete oxidation will only bring about the liberation of a certain balance or residuum of Potential Energy. Acetylene, on the other hand, gives off more heat when burned than its constituent hydrogen and carbon will do; carbon and hydrogen cannot be made by any process, direct or indirect, to combine with one another to form acetylene without the simultaneous supply of Energy: and when acetylene is heated to a sufficiently high temperature, it decomposes explosively with an extremely bright flash, for it is a substance possessing stored-up or potential energy in virtue of a forced combination. The bright flash which occurs in acetylene under these circumstances seems to be, to a large extent, the cause of the Luminosity of Flames. In the formation of bisulphide of carbon, by passing sulphur-vapour over white-hot carbon, a liquid product is obtained. The carbon is liquefied by the chemical combination: the absorption of Heat due to this cause is, on the whole, greater than the liberation of Heat which is due to the satisfaction of chemical affinities between the carbon and the sulphur; and thus, in order to prevent the process of combination coming to an end, Heat must be continuously supplied. On the other hand, carbon-disulphide vapour can be exploded by a fulminate detonator; and the carbon and sulphur then fall apart, with a bright flash and the evolution of Heat.

Oil of lemons, turpentine, and terebene all have the same percentage composition; but when they are burned, so as to form carbonic anhydride and water, equal weights of them evolve different amounts of Heat. This shows that these three substances possess different amounts of chemical energy, and hence the Potential Energy of the molecules is different, so that the intra-molecular arrangement of the mass must be different.

Temperature

When we add Heat to a body, its Molecules bustle about and spin and twist and vibrate more energetically than before: the body becomes **hotter**; or, as is said, its **Temperature** rises. This increase of Temperature is an **effect** of the addition of **Heat**, and it is not to be confounded with the Heat itself, the Energy which is imparted to the molecules of the body.

The Temperature of a body depends upon the **concentration** of Heat-Energy in the mass of the body; that is, upon the number of units of heat per gramme. In different substances, it also depends upon another factor called the **specific heat**; but in order to defer consideration of this, we confine ourselves in the meantime to masses of the same substance, say iron. If a lump of iron weighing say 10 lbs. be kept in boiling water for some time, it will, on being taken out, possess a certain amount, a certain number of units of **Heat**; if the same amount of Heat could by any means be concentrated in a single lb. of iron, that iron would be at a very high **temperature**, for it would be so hot that it would fuse and even boil. The **quantity of heat** would be the same in the 10 lbs. and the 1 lb.; but the **temperatures** would be widely different.

We might find an analogy if we took two equal quantities of salt, and with the one made a small quantity of very strong brine, while with the other we made a large quantity of very weak salt water; the Quantities of salt in both would be the same, but the saltness or **salinity** of the brine would be greater than that of the weak salt-water. If now we had any instrument for finding the *salinity* of the brine and of the weak salt-water respectively, we would be in a position, if we pleased, to calculate the quantities of salt in the two solutions respectively; but we would not be told this by the use of such an instrument alone. The ordinary **thermometer** is analogous to such an instrument; it tells us the **temperature**, but does **not** directly tell us the Total **Quantity of Heat** in the body examined.

One effect of a difference of temperature between two bodies is that **Heat tends to travel from** the body of **higher temperature to** the body of **lower temperature**; and hence the Temperature of a body has been defined as the relative condition of the body under which Heat tends to travel towards or from it.

Temperature is analogous to Pressure in Fluids; for these tend to travel or flow from places of higher to places of lower pressure.

Temperature is usually measured by a **Thermometer.** In this instrument we have a quantity of mercury which occupies known volumes at known temperatures, and the apparatus is so contrived that the **volume** occupied by the mercury can always be readily ascertained.

Suppose we have a quantity of **melting ice,** and a Thermometer immersed in it; the thermometer comes to assume the same temperature as the melting ice, that is, 0° C. In this state of affairs, the thermometer and the melting ice being at the same temperature, there is **equilibrium**; and when equilibrium has been reached, the mercury in the thermometer retains the same volume, so long as the melting ice retains the same temperature; that is, so long as there remains any ice to be melted. Now put this ice-cold thermometer into **warm water**: the warm water is cooled, the cold thermometer is warmed; during the warming of the thermometer the mercury in it undergoes continuous expansion; ultimately both the water and the thermometer come to assume a **common temperature,** and then the mercury ceases to expand. The **volume** which the **mercury** now occupies is known to correspond to a particular **temperature** on the **scale** engraved on the instrument; and thus the Temperature may be measured. But observe that the temperature indicated by the thermometer is **not the original** temperature of the warm water; it is the **common temperature** assumed by the warm water and the thermometer. If we used a large thermometer to ascertain the temperature of a small quantity of water, we would fall into error; for the common temperature attained would be greatly lower than the original temperature of the water: but if we used a very **small** thermometer to ascertain the temperature of a large quantity of water, then our error would be very small; for the common temperature attained would in that case differ very slightly from the original temperature of the water. A thermometer left inside a **closed chamber**, the walls of which are at a certain temperature, will, if no disturbing cause intervene, assume the **temperature** of those **walls**, even though not in contact with them. Heat radiates from the walls, and warms the thermometer.

In all cases a Thermometer must have some sort of a **scale** attached, in order to show the numerical value of the Temperature observed. Therefore we have to make ourselves acquainted with three scales employed, the **Fahrenheit**, the Celsius or **Centigrade**, and the **Absolute Centigrade**.

1. In the construction of a Thermometer which is to be graduated according to the **Fahrenheit** scale, the first essential is a **tube** of **fine uniform bore**. The tube should be "calibrated," that is, tested for the uniformity of its bore, by a drop of mercury being made to travel from one part of the tube to another; this drop should occupy equal lengths at all parts of the tube. At one end of the tube a **bulb** is blown. This bulb is **heated** gently, while the open end of the tube is dipped under mercury. The air in the bulb expands, and partly escapes. The flame which heats the bulb is withdrawn; the heated air in the bulb then cools and contracts, and Atmospheric Pressure drives some mercury up into the tube and bulb. The mercury in the bulb is then heated until it boils, and the open end of the tube is again dipped under the surface of mercury. When the flame is next withdrawn from the bulb, the bulb becomes nearly filled with mercury. This process is repeated until **bulb and tube** are completely **filled with mercury**. The thermometer is then **heated** to something slightly above the highest temperature to which it is intended to expose the instrument. The tube is fused

and **closed**, at a suitable distance from the bulb. This operation in glass-blowing requires some skill, and for ease in accomplishing it, a funnel-head is generally blown on the open end of the tube, as a preliminary to the series of operations just described. We now have the tube, the bulb, and the mercury completely filling these. The instrument next cools, and the mercury shrinks towards the bulb, leaving a **vacuum** at the upper end of the thermometer. Next comes the **graduation** of the thermometer, an operation usually deferred for some months, so as to allow the glass of the bulb to settle down into its ultimate form. The instrument has its bulb immersed in the **steam** from briskly-boiling water; the mercury stands at a certain height in the tube and, at that height, a mark is made on the tube. The thermometer then has its bulb immersed in **melting ice**, and the height at which the mercury now stands is similarly marked. If the bulb be too large, the mercury may retract into the bulb before this temperature is reached; in which case the instrument is unsuitable for low readings. Next, in order to graduate the instrument, the melting-ice point is marked "**Freezing Point**," 32°; the steam-point is marked "**Boiling Point**," 212°; and the interval between these is **mechanically divided** into 180 spaces or **degrees, equal** in length. The division is carried on, above 212° and below 32°, to the top and bottom of the tube, the graduation marks being equidistant throughout the scale. The instrument so made is a **Fahrenheit** Thermometer.

2. In the Centigrade Thermometer the instrument is made in precisely the same way, but the **boiling point** of water is marked **100°** and the **freezing point** of water is marked **0°**.

On comparison of these two scales it is not difficult to deduce a **rule** for translation of any Temperature, given in degrees of the one scale, into degrees of the other scale. For example: what is 98°·4 F.? It is 66·4 Fahrenheit degrees above the freezing point of water (32° F.): but 180 Fahr. degrees are equal to 100 Centigrade degrees: therefore the temperature is $\frac{66\cdot4}{180} \times 100 = 36\cdot8\dot{8}$ Centigrade degrees above the freezing point of water: that is, it is $36\cdot8\dot{8}$ C. Again, what is 40° C.? Since 100 Cent. degrees are equal to 180 Fahr. degrees, 40° C. is equal to $\frac{40}{100} \times 180 = 72$ Fahr. degrees above freezing point: that is, 72 Fahr. degrees above 32° F., or, in all, 104° F. Again, what is −40° F.? It is 72 Fahr. degrees below 32° F.: it is therefore $(72 \times \frac{100}{180})$ or 10 Centigrade degrees below 0° C.; that is, it is −10° C.*

3. The Zero of both these scales is purely arbitrary: and the question arises, What would be the meaning of a **true zero of temperature**? If the Temperature of a body were zero, there ought to be no temperature at all, and therefore **no heat-energy** in the body. This is an unattainable state of things; but it gives an indication as to what Absolute Zero would be.

The Heat present in a perfect Gas is proportional to the product pv, pressure-per-sq.-cm. into volume-per-gramme; but this product is itself, by Boyle's and Charles's Laws, proportional to $(273+t)$, where t is the Centigrade temperature. The Heat present will therefore be *nil* when $t = -273°$ C.; for then the expression $(273+t) = 0$. But when the Heat present is *nil*, the Temperature will be *nil* also.

The **temperature** is a true or **absolute Zero** at **−273° C.**; and physicists make considerable use of a scale—the **Absolute Centigrade** scale—in which −273° C. is reckoned as Zero, and the freezing point of water is called 273° Abs., while the boiling point of water (100° C.) is called 373° Abs.

The law that the product pv varies as $(273+t)°$ C. is then simplified, by conversion into the statement that pv varies as $\tau°$ Abs., that is, that pv varies as the Absolute Temperature. Further, the Absolute Temperature of a body and its molecular Heat-energy are directly proportional to one another; and therefore the mean Velocity of the molecules of a gas is proportional to the *square root* of their Absolute Temperature.

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* $x°$ F. $= \left\{(x-32) \times \frac{5}{9}\right\}°$ C.

$y°$ C. $= (\frac{9}{5}y + 32)°$ F.

The principal kinds of **thermometers** which interest us are **mercury thermometers**, such as have been already described. **Alcohol** thermometers are used when very low temperatures are to be registered, for the alcohol does not freeze: **glycerine** thermometers have been used for the same purpose. The **advantages of mercury** are that it takes but little Heat to bring it to a comparatively high Temperature, that it has a very uniform rate of expansion between −36° C. and 100° C., that it has a low freezing point, and that it can readily be obtained pure. The **whole** of the mercury in a thermometer ought to be at the **same temperature**: else the portion in the tube is cooler than that in the bulb, and the instrument gives on the whole too low a reading.

The **sensitiveness** of thermometers to small differences of temperature is increased by narrowing the tube. Enlarging the bulb would have the same effect; in that case the bulb should be made cylindrical, so that it may more readily enter apertures: but it may, through its size, materially alter the temperature of the object tested, and is then also somewhat slow in its action.

The thread of mercury may be made more **easily visible** by making the tube of flat elliptical section or flattening one face or aspect of it, and enamelling the tube at the back.

The **range** of **mercury thermometers** has recently been **raised** as high as 550° C. by the use of **hard** Jena **glass** and the employment of **nitrogen**, instead of a vacuum, in the upper part of the tube. At that temperature the internal pressure of the nitrogen and mercury-vapour amounts to as much as 20 atmospheres; and this checks evaporation from the mercury. On the other hand, a **fusible alloy** of potassium and sodium has also been used for high-temperature thermometers.

It is found that the Atmospheric Pressure slowly **compresses the bulb** of most thermometers, so that the mercury comes to stand higher than it should; the "zero rises" in this way continuously but slowly, even for years, and old medical thermometers are sometimes found to be as much as 0°·5 to 0°·7 C. in error from this cause: but it does not so rise to any noteworthy extent in thermometers made of the new Jena glass, which bear a distinctive longitudinal red filament of glass. These thermometers are tested against air-thermometers.

Long heating of an ordinary thermometer to 300° C. may so far soften the bulb that the **zero rises** to 14° C.; that is, at 0° C. the instrument stands at 14° C. Strong heating of a thermometer for a **short time** may **lower the zero** by causing expansion of the bulb, which the instrument may take months to recover from.

In a **maximum thermometer**, above the mercury is a small bubble of air; above this a small thread of mercury. The air tends to dilate and push up the thread of mercury, but Friction keeps this in place. When the temperature rises, the air is sufficiently compressed to force the thread of mercury up: when it falls the thread of mercury does not return.

In a **minimum thermometer** the liquid employed is alcohol, and a little broad-headed piece of wire lies loosely in the liquid. As the liquid contracts, surface-tension pulls the wire down: as it again expands, the liquid flows past the wire: and the end of this nearest to the surface of the liquid indicates the point to which the surface of the liquid had shrunk.

In **metastatic thermometers**, a little mercury can be withdrawn from the working mercury in the bulb and tube, by being shaken off into a cavity at the apex or side. There is then less mercury in the bulb and tube, and higher temperatures can be measured with what remains.

For observations of the **temperature** of the **skin** it is well to use quickly-acting thermometers, kept closely in contact with the skin, and covered, at a little distance from the bulb, with a little cupola of cotton or paper. Breathing on the bulb would disturb the reading; covering the thermometer up with flannel and then leaving it too long a time would tend to make the temperature assumed that of the interior, not that of the skin itself.

Specific Heat.—The effect of equal quantities of Heat in raising the Temperature of equal quantities of different substances is not in all cases the same. A kettleful of mercury would much sooner attain a Temperature of 100° C. when placed on a fire than a kettleful of water will do; **less** Heat is required in order to heat **mercury** than to heat **water.** We have seen that this is one of the advantages attendant upon the use of mercury, as the liquid in a thermometer. This is expressed by saying that water has a higher **Specific Heat** than mercury, and mercury a lower specific heat than water. We must, however, have some **standard of reference**; and the standard in use is the **specific heat of water**, which is taken as **unity.** That is to say, we take as our measure of Specific Heat the quantity of Heat required to heat 1 gramme of the given substance through 1° C.; in the case of water this is 1 **calorie**; and so, **measuring in calories per gramme,** we say the Specific Heat of Water is 1. A gramme of mercury is raised through 1° C. by 0·033 calorie of heat imparted to it; hence it is said that the specific heat of mercury is 0·033. The specific heat of copper is 0·95; that of iron is 0·114.

Let us suppose that 100 grammes of water at 100° C. and 100 grammes of mercury at 0° C. are mixed: what will be the resultant Temperature? If shaken together the water and the mercury must come to the same temperature, the water being cooled and the mercury being heated. Let this temperature be t° C.; then the mercury has been heated through t° C., and the water has fallen in temperature through $(100-t)$° C. The quantity of Heat which the **mercury has gained** is (at 0·033 calories per gramme per °C.) equal to $0·033 \times 100 \times t° = 3·3\,t$ calories; that which the **water has lost** is (at 1 *ca* per grm. per °C.) equal to $1 \times 100 \times (100-t) = 10000 - 100\,t$. These must be **equal** to one another, for the heat which the one gains is the heat which the other has lost; hence we have the simple equation $3·3\,t = 10000 - 100\,t$; and on applying the ordinary rules to this, we get the answer that $t = 96·8$. The **common temperature** attained is therefore 96°·8 C.

Again, if 100 grammes of water at 90° C. are shaken with a sufficient quantity of mercury at 10° C., the common temperature may be, say 50° C. What is the appropriate **quantity of mercury?** Here we have the mercury raised through 40° C.; we do not know the quantity of mercury, but let us call it m grammes; the quantity of Heat taken by the mercury from the water is $0·033 \times 40 = 1·32\,m$ calories. The water, 100 grammes, has fallen through 40° C.; the quantity of Heat lost by it is $100 \times 1 \times 40 = 4000$ calories; whence $4000 = 1·32\,m$, and $m = 3030$ grammes. Under the given conditions, then, 3030 grammes of mercury would be raised to a temperature of 50° C., while the 100 grammes of water would be cooled to 50° C.

The same ultimate temperature would be attained, with the same cooling of the original hot water, if instead of using 3030 grammes of mercury at 10° C. we used 100 grammes of water at 10° C. 3030 grammes of mercury are thus, in problems of this order, **equivalent** to 100 grammes of water, and 1 gramme of mercury is equivalent to 0·033 gramme of water.

To **find the specific heat** of a substance, we use precisely similar methods. Let our aim be to find the specific heat of iron. Into 1000 grammes of water at 100° C. we put, say 100 grammes of iron at say 10° C.; the temperature of the water falls to say 92°·17 C. as ascertained by a thermometer. Then the water, 1000 grammes, has fallen through 7°·83 C.; and the Heat lost by the water is 783 calories. The Heat gained by the iron is 100 grm. $\times$ 82°·17 C. $\times$ the unknown specific heat σ, that is, (8217σ) calories. Hence $783 = 8217\sigma$; and $\sigma = 0{\cdot}114$, the specific heat of iron.

To what temperature would one calorie of Heat raise a gramme of iron? Ans. 0·114 calorie would raise it through 1° C.; therefore 1 calorie would raise it through 8°·77 C.

In a **water-calorimeter** we must allow for the **vessel** containing the water. If this be of copper, whose sp. heat is 0·95, and whose weight is C grammes, while the water itself is W grammes, the whole calorimeter is equivalent to $\{W + 0{\cdot}95\ C\}$ grammes of water.

In a **mercury-calorimeter** mercury is employed because, its specific heat being lower, it is more readily heated than water and thus provides us with a more delicate means of investigation.

When a gramme of **hydrogen is exploded** with 8 grammes of **oxygen**, if there be no expansion, 28,580 calories of Heat are liberated. The product is 9 grammes of water-vapour. If we **assume** first that the **specific heat of steam**, which is 0·37 calories per gramme at ordinary steam-temperatures, remains **constant** throughout the temperatures reached during the explosion, and secondly that there is **no loss of heat** to external bodies during the explosion; then we would find that the temperature which we might expect to find developed during the explosion is $28580 \div (0{\cdot}37 \times 9) = 8883°$ C. above the original temperature. No such temperatures are observed, for two reasons; first, the **specific heat** of **steam** (as well as that of most gases) is not constant, but **increases** as the temperature rises; and second, the action does not go on beyond a certain temperature (about 3000° C.) at which the heat would itself effect **decomposition** of the steam produced: so that the temperature approaches this limit, but as it is approached, the combination is **retarded**, and only goes on so fast as will, through getting rid of the surplus Heat by **radiation** and **conduction** to surrounding bodies, enable the products to acquire a temperature which shall not exceed this limit. Hence the **explosion** is more prompt and **rapid** when the **walls** of the explosion-vessel are kept **cool**, so that this surplus Heat is at once withdrawn.

The Specific Heat of **water** is **higher** than that of almost every other substance. There is, however, an exception in the case of **hydrogen**. To heat a gramme of hydrogen through 1° C. requires 2·411 calories if the Volume of the gas be kept constant, and 3·409 calories if the gas be allowed to expand under a constant external Pressure while being heated.

We have already drawn attention to the fact that Gases are more difficult to heat, and their Thermal Capacities are accordingly higher, when they are allowed to expand under a constant external Pressure than when they are maintained at constant Volume, by confining them within a non-expansible vessel. The reason for this is, simply, that when they are allowed to expand they have some external Pressure to overcome, and in overcoming this pressure they do Work; then, in order to enable them to do this work, Heat must be supplied to them, in addition to that which is required for the mere purpose of raising their Temperature. (See pp. 83 and 109.)

Thermal Capacity is simply another name for **specific heat**; but we usually understand that when we use the expression Thermal Capacity we measure the Heat in **ergs per gramme**, while when we say Specific Heat we measure in **calories per gramme**, or else content ourselves with a mere numerical comparison or **ratio** between the Heat required to heat **the substance** in question, and that required to heat an equal weight of **water**.

There is a noteworthy relation between the **specific heats** of different Chemical Elements and their **molecular weights**: this is, that they are, approximately, **inversely proportional** to each other.

In theory this ought always to be exactly the case if there were no Energy given up by a molecule by reason of the combination of its constituent atoms, and no Energy stored up in a mass by reason of intermolecular forces; for according to the Kinetic theory of Gases, **all molecules** should possess the **same heat energy** when at the same Temperature; a molecule of hydrogen the same as a molecule of oxygen, for example; but the number of molecules in a gramme of hydrogen is sixteen times as great as the number of molecules in a gramme of oxygen: whence a gramme of hydrogen would require sixteen times as much Heat to heat it as a gramme of oxygen would, and the Specific Heat of hydrogen would be sixteen times as great as that of oxygen.

If we take, of any element, a number of grammes numerically equal to its Atomic Weight, for instance 35½ grammes of chlorine, we have what is called the "gramme-atom" of that element; and the general law is that it takes neither much more nor much less than 6·4 calories to heat one gramme-atom of any element through 1° C. This is otherwise expressed in the form of Dulong and Petit's Law, that the product of the Specific Heat into the Atomic Weight of an element is always about 6·4; so that the Specific Heat of an element may be used as one means among others for ascertaining its atomic weight.

The rule is only roughly approximate, however; the various elements are, as we usually encounter them, in different physical states: in the metals, in sulphur, and in phosphorus the rule is fairly well obeyed; but in carbon, silicon, and boron the specific heat is considerably smaller than we would expect, until we come to high temperatures, at which the specific heat rises so that the law comes to be more nearly obeyed, the product being then about 5·5.

In the case of solids, the specific heat is not materially increased, as it is in the case of Gases, by the necessity of providing Energy to do exterior work upon expansion; but there is some interior work to be done in separating the molecules, and this requires an extra supply of Heat, known by the name of the latent heat of expansion. This does not affect the Temperature.

Conduction and Convection of Heat

Conduction of Heat.—When we heat one end of a bar of any material, we mostly find that the bar, in a shorter or longer time, becomes warmed along its length; there has been a Rise of Temperature in its substance. Different substances differ in the rate at which a given temperature can travel along them; thus a given temperature will travel faster in copper or in silver than in iron; an iron spoon will still have a cool handle when a copper or silver spoon of the same size dipped in the same hot liquid may already be uncomfortably hot. The rise of Temperature at any given point is due to the fact that **Heat** has **travelled** through the substance, by communication of Energy from particle to particle; but it **does not follow** that a substance in which the Temperature has travelled most rapidly is the one which has conveyed the greatest **quantity of Heat** from the point at which Heat was applied.

The Temperature at a given point depends not only on the **heat-energy** per unit of volume, but also on the **density** and the **specific heat** of the substance itself: and these may, from substance to substance, differ in such a way as to produce anomalous results. Thus if we cut out a little disc of bismuth and one of iron, and coat them with wax and pass a hot wire through the midpoint of each, the wax will melt on each, and the melting will spread over the wax more rapidly in the disc of bismuth. Therefore a given Temperature travels more rapidly in this metal than it does in iron; and yet the other metal, iron, is the one which conveys or conducts the Heat-Energy the more rapidly. The higher density and the higher specific heat of the bismuth have, however, disguised this fact, by minimising the Temperature-producing effect of the Heat conducted. Curiously enough, even **air** is a better conductor of a given Temperature than **copper** is; though when considered as a medium for conveying Heat-energy, tranquil air is an exceedingly bad conductor.

We have therefore to distinguish between a **Flow of Heat** and a **Flow of Temperature.**

Suppose a block of copper, say 10 cm. thick and 10 cm. × 10 cm. in each of its faces A and B (Fig. 128); and suppose that its two opposed faces A and B form the walls of two **tanks** C and D; while the block AB is **jacketted** by felt, or otherwise, so as to prevent any Heat from escaping outwardly; and let us suppose that the tank C is filled with **melting ice**, while D is empty, and that the copper block is itself wholly **ice-cold.** Now fill the tank D with **boiling water**, and let us keep

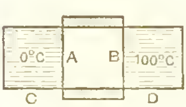

Fig. 128

that water boiling. The face B of the block is promptly heated to nearly 100° C., while the bulk of the block remains at first ice-cold; but **Heat travels** in the block, and at any given point in it the Temperatures go on progressively rising. We may make a diagram, Fig. 129, to show the way in which the Temperature in the block is distributed after successive intervals of time. It takes some time for an appreciable rise in temperature to reach any given point in the line AB; but if we study any particular point such as E, we find that at the successive periods 2, 3, 4, 5, its Temperatures are progressively higher and higher, until a point on the **straight line** AF has been attained. The condition ultimately attained is that the Temperatures in the block fall away **uniformly**, so that at a point say half-way between B and A it is 50°. The **Temperature-Line** FA is then a Straight Line and presents a uniform **slope**; but until that condition is attained, say when the temperatures in the block are those represented by lines 1, 2, 3, 4, these Lines are curved; and so long as they are **curved** there is a **flow of temperature** as well as a flow of Heat. When the line AF has become **straight**, the Temperatures settle down and remain **the same**, so long as the water in the tank D is kept at 100° C., and the mixture in the tank C remains at 0° C. Then the line FA has a certain slope, the Temperature-Slope: and when this temperature-slope has become uniform, Heat is **conducted** steadily through the copper from the boiling water to the melting ice; but the flow of Temperature has then ceased. The quantity of ice melted shows how much Heat is travelling. It is found that the quantity of ice melted is such as to show that, across each sq. cm. of the face A or the face B of the copper block, there pass (0·88176 × 10° ÷ AB) or 0·88176 *ca.* per second; that is, since the area of these faces is 100 sq. cm., 88·176 calories per second in all. This number 0·88176 is a number called the **Coefficient of Conductivity** of Copper; if the block were of **iron** the corresponding number would be only 0·15123; iron allows less Heat to pass than copper does, and is a **worse conductor.** The general law for a slab acting as a conductor is, Heat conducted (measured in calories) $= \theta . A . \delta\tau/d$, where θ is the Coefficient of Conductivity proper to the conducting material, A is the cross-sectional Area (in sq. cm.), $\delta\tau$ is the difference of temperatures (in ° C.) between the opposed faces or ends, and d is the distance (in cm.) between these. In this expression, $\delta\tau/d$ is the Temperature-Slope.

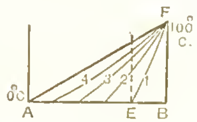

Fig. 129.

For **ordinary rock** the coefficient is only 0·0045; and with the observed temperature-slope of about 0·00033̇ C. per cm. (corresponding to a rise of 1° C. per 30 metres of vertical descent), the Flow of Heat from the **interior of the earth** is, per sq. cm., $0{\cdot}0045 \times 0{\cdot}0003\dot{3} = 0{\cdot}0000015$ calorie per second, or 47·3 calories per annum; only enough, per annum, to melt a layer of ice 0·644 cm. or about ¼ inch thick. We therefore depend now only to an **inappreciably small** extent upon the **internal heat of the earth** for the warmth necessary to render our globe suitable for the maintenance of life on its surface.

During **hot weather**, the **surface** of the soil becomes **warmer** than the subsoil beneath. The difference of temperature causes a flow of heat downwards; but this flow is so slow that at a considerable depth, say 20 feet, it is nearly the end of the ensuing **winter** before the influence of the **summer's heat** is felt: and similarly it is nearly the end of the summer before there appears a fall of temperature due to the preceding winter's cold. The **fluctuations** here alluded to are but **small**, and rapidly become smaller at increasing depths. During the winter there may, in **keen frost**, be a difference of temperatures amounting to say ½° C. per cm.; and the Flow of Heat from the subsoil, due to the surface variations of temperature, is then very considerable, so that the **subsoil** becomes **cold**. **Water pipes** laid too near the surface may thus become frozen: but if they be laid at a **sufficient depth**, the whole frosty season may pass over before any temperature at all approaching the freezing point is attained by them. The earth then acts as a badly conducting felting or **blanket**, and the water in the pipes is not frozen. In Canada and Russia the water pipes are laid at a depth of about 12 feet, and frozen water-mains are practically unknown.

If **two currents** of liquid or gas pass a heat-conducting partition in **opposite directions**, they may almost completely **exchange temperatures**: for at every point the current which enters at a low temperature is at a lower temperature than the current which is passing in the opposite direction in its immediate neighbourhood. This principle is applied in the recovery of the Heat of waste industrial products of all kinds, and in regenerative heating of air for buildings.

We have thus seen that substances such as copper, air, and rock, may differ very much in their conductive power or **conductivity**. A vacuum is perhaps the worst of all conductors of heat; down, hare's fur, sand, asbestos, air, are examples of very bad conductors. Metals, on the other hand, are mostly good conductors.

When a hot body is surrounded by one or more concentric jackets with layers of air between them, the loss of heat is remarkably diminished. A single layer of linen diminishes the loss of heat from the human body by about two-thirds; a double layer effects a much greater economy of heat. Hence the number of garments is of more importance than their weight: and the heaviness of clothes is an incident to the thick film of comparatively stationary air which lies in their spongy meshes. In order that the wind may not displace this, the cloth has to be thick and therefore heavy. The use of double windows, in which a stratum of air stands between the two frames, proceeds on the same principle.

It is impossible to keep the hands in water at 52° C., while it is quite possible, as observed by Banks, to remain for five minutes in air near the boiling point of water.

A test tube containing cold water may have the upper part made to boil by being held over a flame. The heated portion of the liquid is lightest, and floats at the top. Even if ice were made to lie at the bottom of the tube, it would not melt for a very long time, if at all.

Flannel or cork appears warm when touched by the skin on a cold day, cool on a warm day, because it carries from or imparts to the skin less heat than the air had previously been doing.

If the wetted finger be laid on a cold iron railing during hard frost, the iron may carry away so much heat that the water freezes and the experimenter is held fast to the railing.

Convection of Heat.—A hot body, in air, cools down, partly by Radiation and partly by setting up warm air-currents, or **convection-currents**. The air immediately surrounding the body becomes warmed; the warmed air expands and becomes lighter; then heavier colder air flows down and pushes up the lighter heated air. In its turn it again is heated, and is similarly displaced; and thus a continuous **stream** of hot air is set up, rising from a heated body: this hot air soon becomes mixed with the colder air amid which it travels, and the temperature of the whole mass of air thus rapidly becomes uniform. In the **atmosphere** there are continual convection-currents; and it is these which keep the atmosphere well **mixed**, and **uniform** in its composition. Mere Diffusion of Gases would take hundreds of thousands of years to restore uniformity of composition in the Atmosphere, once this was effectively disturbed.

Convection-currents on a great scale may be seen under a large summer **cumulus cloud**: the massive-looking cloud is itself the upper part of an ascending convection-current, the air in which, when it reaches a sufficient height, is expanded so far as to deposit its moisture in the form of droplets, which we see as a cloud. As a rule each droplet is formed round a **particle** of floating **dust**. On the still larger scale, convection-currents are caused over deserts and hot plains by the ascent of heated air: cooler air rushes in from elsewhere; and this gives rise to the disturbances in the atmosphere which we know as **storms**.

On the small scale we may observe **convection-currents** of air by looking along the top of a hot wall baking in the sun, or by looking over the top of a kiln or furnace or boiler; an ascending **column of smoke**, or a **flame**, is an example of a convection-current which bears along with it solid particles of unconsumed or partly consumed fuel; and in **water** we may readily study convection-currents by setting some water in a flask or beaker over a lamp, and throwing in a little sawdust, which will circulate with the convection-currents, descending with the colder water and ascending with the hotter. Convection-currents of air or of water are utilised in Ventilation and in Warming.

Cooling Surface.—The loss of heat by radiation and convection, in free air, depends on the effective Cooling Surface.

In many **stoves** we see radiating sheets of metal attached, which increase the Cooling Surface of the stove, and thereby increase the warming action of the stove upon the air, both by radiation and by setting up currents in the air. In **warm weather** there is a natural tendency to lie at full length, and thereby to increase the cooling surface of the body: in winter the natural tendency is to roll the body up into small compass. The loss of Heat by the **human body** depends upon the **conductivity** of the **skin**; and the flow of heat outwards is practically greatly reduced by a layer of **fatty tissue**. In some cases the **skin** may be warmed, or a continuously abnormal supply of Heat may be brought to it from the internal parts of the body, by increasing the **circulation of blood** in the skin, as for example during exercise or when alcohol is used in cold weather: the skin **feels warm** because the blood-vessels of the skin are fuller than they usually are, and the sensation of warmth is really an indication that the Heat of the body is not being conserved, but is being lost by radiation, convection, conduction, and evaporation at the surface. Such loss of heat may do no harm if the person be well fed, so that there is a continuous supply of Heat-energy from the oxidation of the tissues; but in ill-nourished subjects, or with long exposures to cold, excessive loss of heat from the skin may prove disastrous.

A smaller animal has to produce more heat, per gramme of its substance, than a large one: for it has, proportionally to its bulk, a larger surface-area.

Let us return to Fig. 128, and instead of surrounding the block AB with felting so as to prevent the lateral escape of heat, let us leave its sides exposed to the air. We may suppose this air to be ice-cold, and we may at the same time lengthen our block into a bar or rod or wire, as in Fig. 130. Heat travels along the bar, but is lost in two ways; first by radiation, so that the hand or a thermometer brought near it may be warmed; and secondly by the bar producing convection-currents in the surrounding air. There is, as before, a Flow of Temperature along the bar until a condition of equilibrium is attained: but the Temperatures, when equilibrium is attained, are not such as to present a uniform slope FA as in Fig. 129. The line representing the temperatures at the different points of the bar presents, on the other hand, a form such as that shown in Fig. 131. Near the source of heat the wire is warm, but as we move away from it we find the temperatures rapidly fall off, until, at length, we find that the wire is scarcely heated at all; for the heat which might have gone to warm the wire at any given point has, for the most part, been lost on the way thither. Thus an iron wire 6 feet long may be heated at one end so far as to melt it, while at the other end its temperature is not raised by as much as 1° C. We may burn the most volatile oil in a lamp with a metal wick tube if that wick tube be sufficiently long, for the Heat escapes on its way down the tube from the flame, and the Temperature of the lower end of the wick-tube does not rise to any material extent.

Fig. 130.

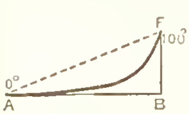

Fig. 131.

A wire heated at one end will not become as warm, at its other end, as a thick rod of the same length would become, for the wire has proportionally more surface exposed. If we want to obtain a given rise of temperature in any part of a piece of apparatus, and find that we can do what is required by means of a rod of metal say 20 inches long, of which one end is in boiling water, and whose thickness is ¼ inch, we can produce the same Temperature (with a slower flow of Heat-energy) by means of a wire of the same metal say $\frac{1}{16}$ inch in diameter but whose length is reduced to 10 inches: for the law is that in bars of different thicknesses, the **distances** from the heated extremity at which the same **temperatures** can be kept up by heating the extremity of the bars to the same temperature are to one another as the *square root* of the **thicknesses.**

Transformation of Heat into Work

When Heat is transformed into Work in a **steam engine,** the **movement** of the **piston** is due to the **bombardment** of its steamward face by the Molecules of the steam. The piston has, at the end of its stroke, to be put back in order to make another stroke; and there is a **limit** to the proportion of the Heat available which can be **converted into work** by any mechanism of this kind. In a particular kind of imaginary engine called **Carnot's engine,** which is an ideal not even approximated to by any engine in existence, the proportion of Heat which could be converted into Work is $\frac{\tau_1 - \tau_0}{\tau_1}$ of the whole, where τ_1 is the temperature of the working gas or vapour, and τ_0 is the temperature to which that gas falls during expansion while doing work, all in degrees on the Absolute scale.

Thus if the working substance became ice-cold on expansion, the temperature τ_0 would be 273° Abs.; if the working substance were high-pressure steam at 120° C., τ_1 would be 393° Abs.: and the utmost proportion of the Heat-energy of the high-pressure steam which could be transformed into Work is $\frac{393-273}{393} = \frac{120}{393} = 30{\cdot}5$ per cent of the whole. In actual steam-engines the proportion transformed into work is much less than this. In a **gas-engine** the hot expanding gas is heated by internal combustion during the explosion, and the temperature τ_1 is much higher (some 1000° C.) than can be applied to steam; so that the ratio above mentioned is larger, and the efficiency of a gas-engine may be greater than that of a steam-engine. On the other hand, the **expansion** of Steam is associated with **condensation,** and this with liberation of energy during the liquefaction, so that the temperature does not fall as rapidly during the expansion as it would do in a gas; and accordingly, expanding steam does more Work than an expanding gas would do.

The statement of the above Ratio is known as the **Second * Law of Thermodynamics.** The Second Law of Thermodynamics also takes the form, which is really another way of presenting the same fact, that Heat cannot of itself pass from a colder to a hotter body, nor can it be made so to pass by any inanimate material mechanism; and that no mechanism can be driven by any simple and simply reversible cooling of any material object below the temperature of surrounding objects. Whether this law applies, or ought to be expected to apply, to animate material mechanism is not yet clear. About fifteen per cent of the total energy of the food consumed is capable of being utilised as Work; and this is a proportion much greater than corresponds to any apparent differences of temperature within the human body, if the body be considered as a heat-transforming Engine. It has been suggested that such differences of temperature as may account, in compliance with the law stated, for the great mechanical efficiency of the body considered as an engine may, after all, exist between the microscopic elements of the tissues: and evidence has lately been adduced to show that this is so. But the Energy which is expended by the body in doing Work seems to be drawn directly from the Chemical Energy of the muscles; and the work is not done by the transformation of Heat-energy, as in a steam-engine. If the muscles have no work to do, the Energy liberated during the chemical changes within them, having no specialised form to assume, takes that of Heat as in ordinary chemical processes, and is dissipated; but if they have work to do, the Energy corresponding to the work done may not take the form of Heat.

* The First Law is the statement that Heat can be measured in ergs or in calories, this statement being usually coupled with a definition of the calorie itself.

CHAPTER VII

ETHER-WAVES

We have seen that when an object vibrates *en masse*, it may produce Waves of Compression and Rarefaction in the **air**. We have now to consider **waves in the Ether.** These waves are produced either by the **Vibration of Molecules,** which is their ordinary source, or by **electric methods** which will be mentioned later on. These waves in the Ether are not waves of compression and rarefaction, but correspond to **transverse deformations** or displacements of the Ether, always at **right angles** to the **direction** in which the Wave is travelling. In this part of this book we shall confine ourselves to those Ether-waves which are due to the Vibration of Molecules.

We must in the meantime reserve opinion as to the nature of the radiations discovered by Professor Röntgen, which will be referred to later on.

Whatever increases the **aggregate kinetic energy** of Molecules, increases in the same proportion the Energy of **vibration** of each molecule; and in some way which is not yet fully understood, the vibrating **molecules** pull the surrounding Ether about, and set that **Ether** in **vibration.** They do not simply dilate and contract, but they distort the Ether as they vibrate, and the Waves produced in the Ether are waves of Transverse Distortion. The greater the amount of Energy possessed by the molecules, the more energetically and also the more irregularly and rapidly will they vibrate; and hence, while the molecules of a comparatively **cool** body will give rise only to waves of comparatively **small** Frequencies, those of a very **hot** body will give rise to a **mixture** of waves of many frequencies, up to the **most rapid** known. All these waves are **propagated** through the Ether with **the same Velocity**, about 30057,400000 cm., or 186000 miles, per second. The waves produced by the vibration of molecules range in **Frequency** from about 20,000000,000000 to about 40000,000000,000000 oscillations per second: and the **Wave-Length** (= velocity of propagation ÷ frequency) in Ether, that is in a vacuum, accordingly varies from about $\frac{1}{1,300000}$ cm. to about $\frac{1}{670}$ cm. The waves are therefore very small: and their presence is a matter of **inference** from the phenomena to which they give rise, especially the phenomena of **Light**.

The Ether-waves, as they travel through the Ether, are all alike in every respect except that of Size: and in that respect they may differ in (1) **wave-length** and in (2) the **amplitude** of vibration.

Waves differing in Wave-length differ in the kind of **effect** which they produce when they impinge upon a solid body. Within a particular **limited range** of Frequency—392,000000,000000 to 757,000000,000000 per second—if they fall upon the **eye** they produce a sensation of **Light**. Of these, the **slowest**—the waves with the least Frequency and the greatest Wave-length—produce a sensation of **red** light; as the frequency increases the sensation produced by them is successively that of what we call orange-red, orange, orange-yellow, yellow, yellow-green, green, greenish-blue, blue, blue-violet, and violet light. Waves of **greater frequency** than those which produce a sensation of **violet** do **not** produce any sensation in the **eye** at all; but they do affect a **photographic plate**; they induce chemical action and are called **Ultra-Violet** or **Actinic** waves.

Note, however, that there is **no** fixed line of **demarcation** between light-producing and actinic waves; the former may also give rise to chemical reactions; but their effect is not, with the majority of substances "decomposable by light," as great as that of the shorter ultra-violet waves. Ether-waves too **slow** to be visible are called **infra-red** waves; and they are very effective in **heating** a body upon which they fall; their Energy is taken up by the molecules of the body upon which they impinge, and the body becomes hot. Note again, however, that there is no line of demarcation between the infra-red waves and the other kinds mentioned: for light-producing or luminigenous waves can heat a body upon which they fall, and even the infra-red waves can effect chemical decomposition in particular chemical substances, so that for example, Major Abney has succeeded in making a photograph of a hot kettle by means of specially prepared photographic plates, exposed to the invisible infra-red waves radiating from the kettle. As it happens, however, the Energy of the longer waves, as we find them in sunlight, enormously exceeds that of the luminigenous waves, and they are therefore more powerful in their heating effect; and they are distinctively called **Dark Heat-Waves**.

These kinds of waves may be produced all at the same time, by the vibration of molecules; and the greater the kinetic energy of the molecules, that is the **higher** the **temperature**, the greater is the tendency to the formation of **light-waves** and **actinic waves**.

When the rare and infusible earth called thoria, mixed with a little ceria, is heated in the hot region of a Bunsen flame, we have the bright incandescence of an Auer von **Welsbach mantle**. Other rare earths present analogous effects; magnesia and lime and zirconia have also been variously applied for the purpose of producing luminous incandescence, as in the **lime-light**, in which lime is heated by an oxyhydrogen flame.

The temperature which an **electric spark** causes the air in its track to attain makes that air glow brightly, so that a luminous **flash** is produced.

When a **hydrocarbon** gas or vapour is burned in a **flame**, chemical changes occur: **acetylene** is produced; the acetylene contains much stored-up energy: when heated to a certain temperature it suddenly decomposes, with great evolution of energy: the decomposition is explosive: the temperature of the hydrogen and carbon produced by the decomposition is very high, and a large proportion of the waves into which the surrounding Ether is thrown consists of waves of high frequency; whence the Luminosity of a **candle** or **gas-flame**. Besides this, we have heavy hydrocarbonaceous **residues** from the hydrocarbon molecules, which are heated by the combustion of the hydrogen; they become **white-hot** and emit light, until they meet sufficient oxygen to burn them away, directly or indirectly, into water and carbon-dioxide.

When **chemical union** is rapid enough to **raise the temperature, light** may be produced: copper filings produce a flash of light when dropped into chlorine; phosphorus burns brightly in oxygen. But if the process of chemical combination be slower, so that the Heat liberated during the chemical combination is largely radiated or conducted away as it is evolved, the Temperature therefore not rising materially, the Waves produced may be all **too slow** to produce the sensation of Light.

But not always so: **phosphorus** left to itself in air combines slowly with oxygen, and radiates light-waves: dry wood, during oxidation by **eremacausis** or slow decay, often shines in the dark: so do **fish** in the first stage of decomposition: and many animals have some process of oxidation, not well understood, in which nearly all the radiations are luminous, as in **hydromedusidae**, in the **noctiluca**, in the **glow-worm**, and in the contracting muscle of some marine **annelids**; while some animals actually have the production of Light of this kind under the control of the **nervous system**, as in the **glow-worm** and in a fish called **photichthys**, which has an illuminating organ with which it temporarily illuminates its prey.

The three kinds of Ether-waves are therefore essentially one in their nature; and it is only for convenience that we divide them into dark heat-waves, light-waves, and actinic or chemical waves. Very frequently we hear of dark heat **Rays**, light-rays and actinic rays; but this expression really means the same thing, with this difference, that when we speak of "rays" instead of "waves" we pay less attention to the mechanism by which the energy travels through the Ether, and more to the **directions** in which it travels.

The wider the **amplitude** of the vibration, the greater is the **heating power** of the radiation, or the **brightness** or intensity of the light, or the power of effecting chemical **decomposition**; these being all proportional to the *square* of the Amplitude.

Colour.—A succession of waves of one frequency only, if the Frequency be within the limits of Visibility, produces a sensation of some particular **colour**; just as a succession of air-waves of a particular frequency, within the limits of audibility, produces a Sound of a particular **pitch.** Each **particular frequency** corresponds to a **particular colour**: within certain limits, from about (395×10^{12}) to about (480×10^{12}) oscillations per second, each particular frequency corresponds to a particular kind of Red, the slowest producing the most crimson red and the most rapid the most orange red; but we may group these together and call them collectively the waves of **red** light. So for Orange, all the way from reddish orange to yellow-orange; Yellow, all the way from orange-yellow to greenish-yellow; Green, all the way from yellowish-green to bluish-green; Blue, all the way from greenish-blue to violet-blue; and Violet, all the way from bluish-violet to the limit of visibility.

In what we call the **white light** of **Daylight** there is a **mixture** of waves, of different frequencies. In this light, at sea level, the intensities or brightnesses of the different groups of waves are somewhat as follows:—Red 54, orange-red 140, orange 80, orange-yellow 114, yellow 54, greenish-yellow 206, yellowish-green 121, green and blue-green 134, cyan-blue 32, blue 40, ultramarine and blue-violet 20, violet 5; total 1000. If we take this as

standard daylight, and if the red and orange-red, for example, should come to be present in a larger proportion, or the colours other than red and orange-red in a smaller proportion than in standard daylight, the daylight would be reddish, as it sometimes is in the evening.

Suppose light-waves of **all frequencies** within the limits of what we have called **red light**, from crimson to orange, say from (395×10^{12}) to (460×10^{12}) vibrations per second, struck the eye **simultaneously**, the impression on the Eye would be that of Red light; and it would be an **average red** light. Precisely the same effect would be produced on the Eye if the waves were all of one frequency, an **average frequency**, say about (430×10^{12}) per second. Similarly if we had waves striking simultaneously whose frequencies ran from say (545×10^{12}) to (585×10^{12}) per second, the effect on the eye would be that of a Green, an average green, such as that produced by pure waves of a single frequency of about (570×10^{12}) per second. But now we come upon a curious pheunomenon. If we allow the undulations of the **red** group and those of the **green** group to enter the eye **simultaneously**, the effect on the Eye is neither red nor green, but **Yellow**, such as might be produced by waves of a single frequency of say (520×10^{12}) per second, but somewhat paler or, as it were, diluted with white; and this occurs though there be no yellow light whatever entering the Eye. The **sensation** of **yellow** is therefore **not necessarily** due to the impact of waves of the **particular frequency** which in a state of purity produce the sensation of yellow: for the same sensation may be produced by **mixtures** of waves of other frequencies.

This result is very singular. It is as if when we listened to a chord sounded by an orchestra we heard only one note, of a kind of **average pitch**: in that case our ears would be unable to tell us what instruments were playing, for the same average might be made up in an infinite variety of ways. Similarly, our Eyes do not enable us, in looking at a Colour, to say how that colour is made up, in what way the Ether is vibrating: and the particular impression received by the eye will depend not only upon the Vibrations communicated to it through the Ether, but also upon the **behaviour of the eye** itself, normal or otherwise, when those vibrations impinge upon it. In many persons the impression received is different from that received by the majority of mankind: and such persons are generally **colour-blind**, completely or partially unable to perceive particular colours.

If in a similar way we try to blend **yellow** and **blue** the resultant sensation is not one of green, but of **white**; yellow and blue are called **complementary colours.** Greenish-yellow and violet produce the same result; and so do many other pairs of colours, complementary to one another, and producing **white** when blended.

Suppose we take a yellow piece of glass and a blue one and with these, with the aid of two lamps L, make a **yellow spot** and a **blue spot** on a screen S. We may shift the lamps so that the position of these two spots varies. Make them **coincide**; the result is yellowish-white if the lamp which makes the yellow spot be too near, bluish-white if the other lamp be too near, and pure white if the lamps be at proper relative distances. Yellow light and blue light thus make white light, even though the vibrations producing the yellow and the blue light respectively be not single but **mixed**; a circumstance which emphasises the part played by the Eye itself in the phenomena of Colour.

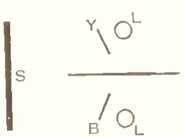

Fig. 132.

If we paint a card half yellow and half blue and **rotate** it rapidly on its centre, it appears a more or less satisfactory white: the impression of the yellow colour has not died away before it is succeeded by that of blue, and *vice versâ*. The two colours are therefore seen **practically simultaneously**, and their effects are **blended** in and by the Eye itself.

If on the other hand we mix yellow and blue **pigments**, we obtain a **green.** The reason is that neither the yellow nor the blue light from pigment is ever pure; both contain **green**: the yellow and the blue form white, but the green remains:

and the result is a Green, which is in such a case always whitish.

All this shows us that when we see light produced, whether white or coloured, we must have some means of investigation other than that afforded us by our eyes alone. Our eyes alone will not enable us to study the **composition** of the light, that is, the presence or absence and the relative strength or feebleness of the different component wave-motions which make up that aggregate wave-motion, to which the sensation of light is due. This superior means of investigation is furnished us by the **Prism**.

Let us fit up a box with a small slit at A; behind A fit up a glass prism B, with its length parallel to the slit; and at the back fit up a ground-glass **screen** C. Turn the whole towards the sun, and on the ground-glass screen there will be seen a **many-coloured band** of light. On a larger scale, this may be done with a **slit** in the shutter of a darkened room, a **prism** immediately behind the slit, and a linen **screen** on the opposite wall; and a mirror may be used outside the window in order to reflect the sunlight horizontally through the slit. For many purposes, however, the simpler apparatus described will serve. The end of the band marked R is red; the end marked V is violet; and between the red and the violet we have all the intermediate colours, orange, yellow, green, and blue. It will also be noticed that the **spectrum**, as this many-coloured band of light is called, is wholly **to one side** of the path which the light would have pursued but for the intervention of the prism. The waves which produce the red components of daylight have been turned aside or **refracted** so as to reach not O but R; the waves of violet have been more refracted, and have found their way to V; waves of intermediate frequencies have gone to intermediate positions. We thus have all the **components** of the sunlight marshalled

Fig. 133.

before us side by side, and we can see what they are. The spectrum is really **longer** than it looks, for the shorter **ultra-violet** waves are refracted to positions beyond V, though we cannot see them: if we replaced the ground-glass screen by a photographic plate we could, however, make a **photograph** of the ultra-violet invisible part of the spectrum. The longer **infra-red** or heat waves, also, are refracted to positions between O and R.

Now let us try to ascertain the **cause** of the **colour**, say of a piece of **green glass**. We look through our apparatus of Fig. 133, and observe our sunlight **spectrum**; then between the sun and the slit A we insert our piece of green glass. All at once a part of the spectrum disappears: the **red disappears**; most of the orange and yellow and some of the blue and violet also fail to come through the green glass, being **absorbed** by it; but the **green part** of the Spectrum **continues** to shine brightly, perhaps with some of the yellow and blue or with traces of the orange or the violet. Different samples of coloured glass will cause different appearances in the spectrum of the transmitted light. For example, some samples of red glass entirely cut off all green light; others will not do so, and are therefore not fit for use as a protection against green light in photographic work; and yet both kinds may, to the Eye, appear equally satisfactory in their depth of red colour.

The Spectrum enables us to find out a good deal about the behaviour of the **molecules**, whose **vibration** originates the Ether-waves. When the vibrating molecules are those of a **gas**, the molecules are fairly **independent** of one another, and their Vibrations are then as simple as the constitution of the molecule will permit them to be. The corresponding Waves are then as nearly **simple** as they can be; and in the Spectrum produced, the light is restricted to mere bright **lines**, which correspond to the narrowest possible images of the slit. As the gas increases in Density, say on **compression**, the molecules hamper one another and the lines spread out into **bands**; and as the compression still increases, the molecules enter into the most **irregular** vibrations. The consequence of this is, that in the light coming from a Solid the lines or bands of the spectrum spread out, so as **continuously** to light up, more or less, the whole region from red to violet.

If we take a **white-hot** iron ball, the spectrum of whose light is **continuous**, and watch its spectrum as the ball **cools**, the **violet end** of the spectrum is seen to **fade away**. This fading away is continued down the spectrum until there is very little left except the **red** region of the spectrum; at that stage the ball is "**red-hot**"; and as the cooling continues, when the temperature falls to about 525° C. this red region of the spectrum also fades away; but the ball still acts as a source of Heat-waves, or "**radiates heat**," as may be felt on bringing the hand near it. It **never** does **cease to radiate heat**; there may, it is true, come a time when it gains as much heat from other bodies as it loses to them by radiation, so that a condition of **equilibrium** is attained; and under **ordinary conditions** this is what continuously occurs: but if into the neighbourhood of bodies at ordinary temperatures we bring a block of **ice**, we see that these bodies are radiating heat: for they cool down while the ice melts. To the ice they act as comparatively **hot bodies**: and the ice does not make up to them for the Energy which they lose to it. Radiation of Heat from a body could only cease if the **molecules** were brought to **rest**; that is, if the **temperature** were reduced to **absolute zero**.

Hence we see how in a **clear** tropical **night** the radiation from the earth may cause so much uncompensated loss of heat that **ice** may form; and how dangerous it would be to sleep outside under such a sky.

Accordingly, Radiation is always going on; and two bodies equally hot **exchange energies** by radiation; but they do this to an equal extent, and there is thus no change in their relative Temperatures. This is **Prévost's Law of Exchanges.** If one body be hotter than the other, the exchange of radiations always tells in favour of the colder until equality of temperature is reached: and the radiation from a body goes on, whatever be the radiation to it from surrounding bodies. The brightness of a candle or the amount of heat radiated from a fire does not depend on the presence of objects to be illuminated or warmed.

When a body is **surrounded** by **hot walls**, the radiation from the body to the walls comes to be equal to that towards it from the walls: then equilibrium is attained; but when this condition has been attained, the temperature of the body enclosed is **equal** to that of the walls surrounding it.

Hence in an **incubator** for eggs, or in a **thermostatic nurse** for prematurely-born infants, the eggs, or the infant, are kept at the same temperature as the walls of the apparatus in which they are enclosed; except in so far as the needful current of air may tend to prevent this temperature being attained.

The amount of **Energy** received by a **surface**, through Radiation from a distant **point**, is *inversely* as the *square* of the **distance** from that source.

A candle at a distance of 1 foot will illumine a printed page as well as a 36-candle lamp will do at a distance of 6 feet.

If the source be a **surface**, the same law is approximately obeyed at sufficiently **great distances.**

A broad illuminating surface, such as a white wall, is equally bright when looked at at all distances through a narrow conical tube. Close at hand it appears brighter, area for area: but at a greater distance more of it can be seen: the aggregate effect upon the observer's eye remains the same.

When we feel too warm near an open fire, we withdraw to a greater distance.

The least amount of illumination which is suitable for ordinary work seems to be about ten "metre-candles"; that is, ten times the illumination produced by a candle at a distance of one metre, or 40 inches.

The Energy received per Unit of Area depends upon the **obliquity** of the receiving surface. If the source be at AB and the waves flow towards CD, if the receiving surface be tilted to the position CE, the energy received per unit of area is to that received in the position CD, as CD : CE ; that is, it varies with the **cosine** of the Angle DCE.

Fig. 134.

The illumination due to sunlight is therefore greatest at noon and falls off as the day advances.

If a body readily **radiate** heat away, it must, in order that the Equilibrium of Temperature between it and surrounding bodies should be kept up, **absorb** as much ; it must therefore be a good absorbent. Conversely, **good absorbents** of the energy of ether-waves are **good radiators** of the same.

A **brightly-polished** metal vessel is a **bad absorbent**, as is shown by the circumstance that it is a **good reflector** : being a bad absorbent it is a **bad radiator**, and it will retain a high temperature a long time, much longer than a thinly-blackened surface will. If soot be sprinkled upon snow, the snow will readily melt in the sun's rays : for the soot is a good absorbent and itself becomes heated.

The Law of **exchanges** applies not only to the aggregate Energy gained or lost by a body through radiation, but is also true of **each particular frequency**. As yellow glass absorbs blue light, so when heated it gives out blue light.

The phenomenon of **Resonance**, which we have met with in relation to sound-waves, applies also to Ether-waves. A set of **molecules** impinged upon by a **mixture** of Ether-waves, of which some have the same Frequency as the natural free vibration of the molecules, will themselves be set in **vibration** ; but in this, they rob the whole wave-system of the **particular component** waves which effect this result. If Light from a white hot iron ball, which has a **continuous** spectrum, be transmitted through the vapour of **sodium**, it is found, on examining the spectrum of the transmitted light, that it now presents a **dark line** in the yellow. A particular kind of Light has been **cut out** from the aggregate radiation; component waves of a particular Frequency have been denied **transit**, and their Energy has been **absorbed** by the sodium-vapour; and the particular Frequency of these waves is precisely that of the waves emitted by hot **sodium-molecules**, as for example, when salt is put in the wick of a spirit-lamp so as to produce a yellow flame. This yellow spirit-lamp flame has a spectrum which consists of nothing more than a bright **band** in the yellow (this band being really double). In **sunlight** there is a **dark band** at this place in the spectrum; which shows that between the hot body of the sun and ourselves there is a cooler **solar atmosphere** containing **sodium vapour**. As in this instance we are able to state the presence of sodium in the solar atmosphere, so in many other instances the presence of particular chemical elements, or even of particular conditions or combinations of these, may be ascertained by means of the **dark lines** produced by **absorption**, or by means of the distinctive **bright lines** of the spectrum produced by **incandescence**. This is the basis of **spectrum analysis**, which implies a practical knowledge of the characteristic bands or lines of each element. In sunlight there are a good many of these dark lines or bands, which are known as Fraunhofer lines.

To obtain an **incandescence-spectrum**, with its bright lines, we may **volatilise** the substance to be examined, in a hot **flame** such as a Bunsen flame, and examine the light of the flame.

To obtain a spectrum showing what light is **absorbed** by a given transparent substance, we transmit a bright white light through that substance, and examine the light transmitted. For example, if a strong solution of

blood be interposed in the path of a beam of light which is on its way to form a spectrum on a screen, all the **spectrum**, with the **exception** of a portion of the **red** part of it, **disappears.** As the liquid is **diluted** the spectrum lengthens out; orange, yellows, greens, blues, are successively added; but there always remain two relatively dark bands ("**absorption-bands**") in the spectrum, in the yellow and in the green, between the dark lines in the solar spectrum known as the Fraunhofer lines D and E. These dark bands are characteristic; and they enable the presence of **hæmoglobin**, and therefore of blood, to be detected.

If the blood be treated with sulphide of ammonium, the hæmoglobin will be **reduced**; its chemical constitution changes, and with it the absorbent power: the absorption band is now a **single band** situated between the two preceding. Carbonic oxide and nitrous oxide also produce distinctive changes in the absorption-spectrum of hæmoglobin.

If we **look at** a solution of **blood** as it is being progressively **diluted**, we find that it is at first red, but becomes more and more yellowish, as well as paler in its hue. The same effect is obtained on looking at layers of **different thicknesses.** If a strong solution of blood be put in a wedge-shaped vessel, the **thicker** portion of the solution looks **red** while the **thinnest** portion looks **yellow.** The reason of this is, that the different colours are absorbed in different proportions by the solution; and small differences in these proportions accumulate, so as to cause great differences in the composition of the light transmitted through different thicknesses.

For example, if we take as our original light four portions of the spectrum of equal aggregate brightness, and if the first mm. thickness of the solution allow $\frac{8}{10}$, $\frac{7}{10}$, $\frac{6}{10}$, and $\frac{5}{10}$ of these respective regions to pass through, the ratios of brightness in the light transmitted by a thickness of 1 mm. will be 8 : 7 : 6 : 5; but the second mm. thickness will only allow $\frac{8}{10}$ of $\frac{8}{10}$, $\frac{7}{10}$ of $\frac{7}{10}$, $\frac{6}{10}$ of $\frac{6}{10}$, and $\frac{5}{10}$ of $\frac{5}{10}$ to pass. At the

10th mm. thickness, the ratios of brightness will be $0 \cdot 8^{10} : 0 \cdot 7^{10} : 0 \cdot 6^{10} : 0 \cdot 5^{10}$, or 0·10738 : 0·02824 : 0·00605 : 0·00098, or about 8 : 2·11 : 0·45 : 0·07. A group of rays which is merely somewhat less readily transmitted by a thin layer is thus, relatively, almost entirely extinguished by a thick layer, and this influences the resultant colour of the transmitted light very greatly. Substances presenting this kind of difference of colours in thick and in thin layers are said to be **dichroic**. **Chlorophyll** appears green in thin layers, red in thick. **Iodine** vapour transmits a blue group and a red group, as also ultra-violet rays; together these produce an impression of purple: through thicker layers the blue is alone transmitted, and the vapour appears blue. **Venous blood**, or a solution of reduced hæmoglobin, appears purple-claret in thick layers, greenish in thin.

If we take a piece of red and a piece of green glass and try to look through **both** at the same time, we find that hardly any light comes through; what the red glass lets through is what the green glass absorbs, and *vice versâ*.

If a substance allow light-waves to pass through it, but will not allow dark heat-waves to do so, it is said to be **transparent** but **adiathermanous**: for example, a crystal of alum. If it allow dark heat-waves to pass through it, but not light-waves, it is said to be **diathermanous** but **opaque**; for example, a strong solution of iodine in bisulphide of carbon, or a very thin film of vulcanite.

Lampblack is very diathermanous to the slowest heat-waves, and **air** very adiathermanous to some of them. **Glass** is very transparent and diathermanous, but is somewhat opaque to the ultra-violet rapid ether-waves; a **quartz** prism or lens allows a great amount of ultra-violet radiation to pass through it which a glass prism or lens would extinguish, so that while with a glass prism the ultra-violet invisible part of the spectrum is comparatively short, with a quartz prism it is from six to eight times as long as the visible spectrum. **Silver leaf**, just thick enough to be opaque to light, transmits ultra-violet rays.

A photograph can be taken through a very thin film of vulcanite or of coal tar; for these substances are largely transparent to ordinary ultra-violet rays.

Glass coloured a greenish blue by **unoxidised** protoxide of iron is singularly **adiathermanous**, and may be used as a heat-opaque **fire-screen**. For **lamp-chimneys** it is not so useful, for the chimneys become hot and themselves radiate heat.

A substance which allows light to pass through it, but at the same time scatters it in all directions, is said to be **translucent**; *e.g.* ground glass. If an electric lamp be held in the mouth, the effect of translucency is very singular; and if it be let up into the post-nasal cavity, it is still more so, for the eyes themselves then appear to glow.

So far as we have treated of the **colour** of coloured objects, it has been the Colour of **transparent** objects, which is due to **absorption** and subtraction of some of the light which endeavours to traverse the selectively-transparent object. The **colour of opaque objects,** as seen by ordinary reflected daylight, is also due to **absorption**. This is not so obvious. A **white** object is one which reflects ordinary daylight without absorption; a **green** object (for example) is one from which the incident daylight is reflected, shorn of a number of its components such as, together, correspond to a sensation of red. The incident daylight having **lost its red** during Reflexion, appears **green** after reflexion. What is it, then, that happens during Reflexion? What happens is that the incident light, or a proportion of it, **travels to a certain depth** below the surface of the coloured object and is reflected there, not at the very Surface itself. In its very short path in the substance of the coloured object it is selectively **absorbed**. On the very small or molecular scale, the phenomenon is one which may be very roughly illustrated on a larger scale by mixing chalk or magnesia powder with a blue solution of sulphate of copper: the mass looks like a bluish cream. The incident light traverses the solution until it reaches a particle of chalk, and is then reflected to the eye; but on its way it experiences the selectively absorbent action of the copper solution, which robs it of red, etc.; so that on emerging it can only be blue. In the same way a piece of blue material reflects light from a little way below its surface: and the greater the thickness through which the light travels before finally emerging on reflexion, the deeper will be the colour produced.

Thus when pigments are mixed with oil, there is less reflexion at any given depth, and the light penetrates farther before being completely turned back than when the same pigments are used as water-colours; so the colours are deeper and richer. Again, if there be but one reflexion, the colour produced is not as deep as if there be many reflexions, but is more mixed with white light reflected merely at the surface; so that a gold vase appears of a much richer tint internally than externally, because of the multiple reflexion which occurs there. If on the other hand we limit the thickness of the film which the light can traverse, we partly eliminate the effect of absorption; and thus if we mix soap with a brown liquid and make soapsuds with it, the froth appears nearly white: or if we grind coloured substances to powder, in many cases they are much paler than the same substance in solid bulk; for example, coloured glass ground to powder is nearly white.

We may produce films of gold leaf thinner than the superficial film within which this absorptive action takes place on reflexion. With such extremely thin films (such as may be made by fixing gold leaf on glass and dissolving some of the gold away by means of a dilute solution of cyanide of potassium), we find that the film is transparent to green or to green and violet light, according to its thickness: the light which passes through appears greenish-blue or blue or violet, the last colour being that of the thinnest films. Films of silver, in the same way, allow a pleasant greenish light to come through; and the object glass of an astronomical telescope intended for solar observations is often very thinly silvered, so that the heat-waves are reflected away, in order to protect the eye of the observer.

There may be cases in which the whole of the light which impinges on the object is absorbed: the object then appears black; that is to say, no light comes from it to the eye. This, in daylight, is the condition of ordinary black objects; but there is hardly any black object which is wholly destitute of reflecting power, and the usual cause of what we call Blackness is not that no light comes from the object to the eye, but that **very little** comes.

The blackest object looks gray in comparison with what is called **Chevreul's black**, which is what we see when we look at a hole in the side of a large box lined with black velvet.

Again, if we use, as our incident light, any particular **kind of light** which happens to be **wholly absorbed** by the object, that object will appear **black**: if for example we look at a yellow and a blue flower by the yellow flame of a spirit lamp with common salt (NaCl) in the wick, the yellow flower appears distinctly yellow, for it does not absorb yellow light on reflexion; but the **blue** flower looks **black**, for it **absorbs all** the yellow light and reflects none of it; and as there is nothing else to reflect, the impression in the eye is that of a black flower.

When sunlight falls on a white wall, actinic or ultra-violet waves are reflected from it along with the light-waves, and what can be seen can be photographed; but if it fall upon green leaves, the actinic waves are mostly absorbed by the leaves, and there is very little of these reflected, so that foliage is very difficult to photograph. There is very little impression made on the exposed plate, and in the resultant photograph, foliage comes out disproportionately dark.

When Ether-waves are **absorbed** by a medium through which they are sent, the **energy** of the **waves** is transformed into **Heat** of the **molecules** of the medium; but what passes through freely does not heat the medium.

In **very clear air**, on mountain tops for example, the sunshine streams through the air without heating it, and the air may be very cold: but if there be **dust** in the air, the dust becomes heated, and this dust then heats the air. Heat-waves may pass through **very clear ice** without melting it: but if there be any dust in it, each particle of dust acts as a centre round which the ice melts, forming star-shaped cavities containing water.

When Ether-waves are absorbed at the surface of a body, the surface becomes warm.

A black suit of clothes becomes warm in the sunlight where a white suit will remain comparatively cool; but being a better radiator as well as a better absorber, a black suit will, upon exposure to a lower temperature, cool down where a white suit would tend still to remain comparatively warm.

When a body has been shone upon by light-waves and thus become warmed, and is then cooled down by radiation, the molecules have been shone upon by **shorter waves**, and have themselves originated **longer waves** of dark heat. Even within the limits of frequency which characterise Light-waves, a phenomenon similar to this occurs, and is called **Fluorescence**. If we take a solution of **quinine** sulphate or dichloride, and pass a beam of light through it, the solution seems **self-luminous** for some distance along the track of the beam of light. Ultra-violet, violet, and blue rays fall upon it and are absorbed; and the molecules are set in **slower vibration,** which gives rise to the sensation of a greenish-blue light, that light which is seen about the edge of a solution of quinine in a phial.

There are a great many fluorescent substances, each of which emits light of a distinctive colour; **petroleum** or shale oil emits a green; a solution of **turmeric** in castor oil a green; **chlorophyll** in solution a red; a solution of **datura stramonium** in alcohol a greenish-blue; **uranium glass** a greenish-yellow. The cornea and the rods and cones of the retina, and the media of the eye, are also slightly fluorescent: and this may account for some persons being able to see some of the ultra-violet. When we take a sheet of paper painted with a fluorescent solution, say one of sulphate of quinine, and use this as a **screen** upon which to form a **spectrum**, we find that the **ultra-violet** rays make the screen shine over an area which, with a quartz prism, is six to eight times as long as the ordinary visible coloured spectrum: and the effect of the ultra-violet rays may thus be rendered **visible**.

If the fluorescence be **continued** for some time after the body has ceased to be shone upon, the substance is said to be **phosphorescent**. A well-known example of this is Balmain's **luminous paint**, which shines in the dark after being exposed to light; and the same property is possessed to a small extent, the luminosity being continued for a short time only, by dry paper, silk, and even the human teeth. The properties of fluorescence and phosphorescence are very widely distributed; and apparently all bodies are phosphorescent when **exceedingly cold.**

Light which has passed through a sufficient thickness of quinine solution cannot cause fluorescence in a second layer: those waves which were competent to set up the fluorescence have been **absorbed.**

If we cause a body to **absorb** so much **radiant heat** that the Energy taken up by it raises its **temperature,** it may become hot, and even white-hot. We may, for example, pass the light from an electric lamp, which is accompanied by radiant heat, through a solution of iodine in bisulphide of carbon; the heat-waves come through, but not the light-waves: these heat-waves may then be concentrated by a lens or mirror upon a solid object, which may become white-hot, and will then emit short **light-waves** as well as longer dark heat-waves. This phenomenon is called **calorescence.**

Apart from this, there are very few cases in which the impact of longer heat or light-waves causes the radiation of **shorter** light-waves. **Chlorophane,** a kind of fluorspar, is an example; it radiates an emerald green light when dark heat-waves strike it: and **chlorophyll** radiates a red light when shone upon by a still slower red light.

The **velocity** of **propagation** of Ether-waves is ascertained by two astronomical and two terrestrial methods, which are used to determine the Velocity of Light. The mean result is that Light-waves travel through the Ether of space with a velocity of **30057,400000 cm. per second**: that light-waves of **different frequencies,** at any rate from red to violet, travel with the **same speed**; and it is inferred that there is no difference between the waves of Light and the longer waves of Radiant Heat or the shorter waves of Actinic Radiation, except in respect of wave-length or amplitude.

Just as we measure the Velocity of Sound by watching the time which elapses between seeing the flash from a distant gun and hearing the belated report from it, so we employ astronomical phenomena to ascertain the Velocity of Light. **Jupiter's satellites** seem belated in their movements when Jupiter is farther from us; and the reverse when he is nearer: the reason being that the light takes a measurable time to come. Again, light actually takes some time to travel down the **tube of a telescope**, so that we have to **tilt** the telescope a very little off the true in order to enable us apparently to look straight at a star, as the earth is being bowled along in its orbit: and this tilt is measurable. Again, we may make light travel between two teeth of a **cogwheel**, go to a distant mirror, be there reflected, and come back: but before it has got back, the wheel may have **rotated** to such an extent as to block its path by means of one of the teeth; and then, if we adjust the speed of the rotating cogwheel so as to allow the light to return through the *next* gap between the teeth, we know how long the light has taken to go and return. Or the light may strike a **rotating mirror**, and go to a distant fixed mirror and back; by the time it has come back the mirror may have rotated so as to reflect it, on its return, not towards the original source but in another direction: and the amount of this deviation of path is measurable.

The **measurement** of the **brightness** of a source of light depends on the law that the illumination, at any place, varies inversely as the square of the distance of that place from the source.

In a **Photometer**, two sources of light are placed at such distances from an illuminated surface that they appear to produce the **same effect**: the illuminations produced by the sources A and B are then proportional to the squares of the distances of A and B. Thus if B be a standard candle at a distance of 1 ft., and A a gas-flame at a distance of 4 ft., if the effects be equal the sources are to one another in the ratio of $1^2 : 4^2$ or $1 : 16$; and the gas-flame is equal to 16 standard candles. The Equality of Effects produced is ascertained by various methods: of these the simplest is that of Rumford, who used the **two shadows of a stick** produced by the two lamps and adjusted until the two shadows appeared similar: but if the lamps give differently coloured light, the shadows seem differently coloured and are difficult to compare. In Bunsen's **grease-spot photometer**, a grease-spot is used in a piece of opaque paper; light from towards the front will make the grease-spot appear comparatively dark: light from behind tends to make the grease-spot comparatively bright; when the distances are properly adjusted the grease-spot disappears. Mirrors are provided which enable both sides of the paper to be looked at at once. Apart from inequalities in the two eyes of the observer, this method would be a sound one, provided that the white paper reflected all the light which fell upon it while the grease-spot itself reflected none, but was perfectly transparent. In **Lummer and Brodhun's photometer** this idea is applied by purely optical methods. A block of glass, Fig. 135*a*, is cut through as in *b*: one prism is then ground away as in *c*; and the two prisms are polished and put together as in *d*. Light from S′, Fig. 135*d*, is seen by an observer at E to be completely reflected from the rim; but the central part appears dark, for the light striking it has gone completely through towards E′, and none is reflected towards the eye. Similarly, light from S would come through the central part to his eye at E, but none would come through the rim. If the lamps at S and S′ be at proper distances the brightness of the rim and that of the central part will be the same, so that no distinction can be observed between them. In practice, instead of lamps at S and S′, mirrors are used at S and S′ to throw light on to the prisms from the opposite sides of a white-paper-covered screen at L, which has its two sides respectively illuminated by the two lamps to be compared: and the distances of these two lamps from this screen give the data required for the calculation. With this instrument only one eye is used.

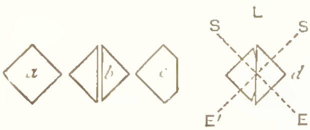

Fig. 135.

There has been a good deal of discussion about photometric standards and methods; one outstanding difficulty is that the law of the inverse squares is only truly applicable when the sources of light are mere **points**; and another is that it is barely possible to obtain equality of effects unless both sources yield light of the **same colour**. Hence it has been necessary to devise instruments called **spectrophotometers**, whereby the brightnesses of the respective parts of the spectra produced by two sources of light may be successively compared.

"**Polarisation of Light.**"—During its transmission through the Ether, the **wave**, being a transverse-distortional wave, is **transverse** to the **direction of propagation**, as though the Ether were being pushed and pulled **parallel to the wave-front**, across the line of direction of propagation of the wave. (We are speaking now of what occurs in **free Ether** or in **air**, not of what happens inside a crystal.)

Suppose A is a source of light-waves, and AB any particular direction along which the waves from A expand. At the point B let us suppose the motion of the Ether to be from side to side, along the paper, at right angles to AB. If the wave-front be broad, the movement will be participated in by the whole wave-front, so that the whole wave-front will swing from side to side, always at right angles to a line drawn from the source A (Fig. 137).

Fig. 136.

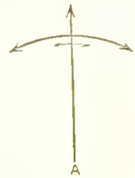

Fig. 137.

If however we confine our attention to what happens at one point B of the wave-front, we are brought back to Fig. 136, and light in which the point B oscillates transversely, from side to side, **in one plane** is called **Plane Polarised Light.**

Next let us suppose the point B to describe a little circle, alternately rising above the plane of the paper in Fig. 136 and sinking beneath it; all points in the wave-front will execute corresponding movements; such light is said to be **Circularly-Polarised Light.**

Similarly if the point B describe little ellipses in the same way, the light is **Elliptically-Polarised.**

Now let B, keeping always at the same distance from A, describe the most **irregular** little transverse movements that we can imagine; the only condition imposed is that there shall be no tendency to vibrate, on the whole, in any one direction any more or any less than in any other: then, whatever B does the whole wave-front participates in; and *this* is the condition of the wave-front in **Common or Natural Light**, ordinary sunlight or lamplight.

The next thing we have to understand is the action of a polariser. In order to understand this we had better look at the point B along the line AB, as a line of sight. Then the movement of B in Fig. 136 would appear to be simply a line executed in one plane; and this is our plane-polarised light.

Fig. 138.

Circularly-polarised light would have its movement correspondingly represented by the diagram Fig. 139 (*a*) or (*b*). But now let us suppose that the wave-front in which the motion is that represented by Fig. 139, finds its way into a region in which oscillation in the direction CD is freely permitted, but oscillation across the plane CD is prevented. The result will be that on emergence from such a region, all the oscillations athwart the plane CD will have been absorbed and extinguished, and only those parallel to CD will come through. The circularly polarised light has then been reduced to plane-polarised light, of *half* the original intensity or energy. The region of space possessing this peculiar property would, in producing this effect, act as a "Polariser." But there are crystals which act in the way imagined: a crystal of tourmaline does act as a Polariser: and any light which finds its way through it emerges plane-polarised, that is, with its vibrations restricted, at any point of the wave-front, to one plane.

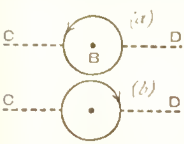

Fig. 139.

A very thin layer of tourmaline may act as a partial polariser: that is, it would not entirely abolish the movement athwart CD, but would reduce it, so that the light would be "partially polarised" and would, in the instance supposed, become elliptically polarised, as in Fig. 140.

Fig. 140.

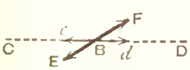

Fig. 141.

Next suppose that the light were already plane polarised, its oscillations being in the plane EF: what would be the effect of the polariser upon it? If thick enough the layer of tourmaline would reduce it to **plane-polarised** light whose oscillations were confined to the **plane** CD; and it would **reduce** its Amplitude of oscillation from BE or BF to Be or Bd.

If EF were originally at right angles to CD, *ed* would have no length at all; the oscillation would have no amplitude; that is to say there would be **no oscillation** transmitted; and the meaning of this is, that the **polariser** would be **opaque** to plane-polarised light oscillating in a plane **at right angles** to CD. This is what takes place if we take **two crystals** of tourmaline, lay them **across** one another, and try to look through them; we see nothing. The oscillations which have come through the first tourmaline are completely intercepted by the second; and thus **crossed** tourmalines produce perfect **darkness.**

When the light is plane-polarised so that its oscillations are confined to the plane CD, it might be expected that if the light in question were said to be plane-polarised in a "**plane of polarisation,**" that that plane of polarisation would be the plane CD. But this is not so. For reasons which are beyond the scope of this volume, plane-polarised light whose oscillations are confined to the plane CD (Fig. 142) is said to be plane-polarised **in the plane** PP′ **at right angles** to CD (that plane being also at right angles to AB, the direction of propagation of the wave), and the **plane of polarisation** is the plane PP′, not the plane CD in or parallel to which the actual oscillations occur.

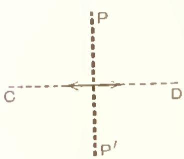

Fig. 142.

Under particular circumstances which will be explained later, the **plane of polarisation** of plane-polarised light may be **rotated,** so that the oscillations swing round as the plane-polarised light travels along. This phenomenon goes by the name of **Rotatory Polarisation**; and it must be understood before we can understand the **saccharimeter,** which is used in estimating the sugar in diabetic urine.

Dark Heat-waves and Actinic waves may be polarised in precisely the same way as the waves of ordinary Light.

Reflexion and Refraction

If a ray of light fall upon a smooth surface of glass or other transparent medium, it is generally both **reflected** and **refracted**: that is to say, if the light travelling in the direction AO strike the glass at O, part of the light is reflected at O in the direction OB, and part is refracted or bent at O, from the direction AA′ into the direction OC.

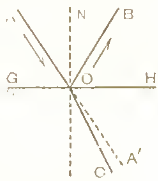

Fig. 143.

We have already seen (pp. 45 and 46) what these directions are. The **angle of reflexion** is equal to the **angle of incidence**: and the **sine** of the **angle of refraction** is equal to the **sine of the angle of incidence** multiplied by the **index of refraction.**

If the incident light travel along a line A_v O, at **right angles** to the refracting surface, it proceeds along the **same line** towards C_v, and is not refracted at all: if it go along $A_/O$, practically but not quite **parallel** to the refracting surface, it will be refracted into a direction $OC_/$ (Fig. 144); and it is not possible for any light to be refracted into any direction between $OC_/$ and OH; for there is no possible Angle of Incidence left which could give us so large an Angle of Refraction.

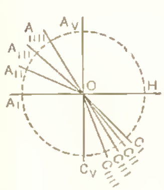

Fig. 144.

If therefore we take a thick **slab of glass** and cover it all except one side and the bottom with black paper, with a small **aperture** in this, in the middle of the top at O: and if we put a layer of white paper at IJ and look in at the side, while the top of the slab is exposed to the **open sky**: we shall see that the paper is illuminated between the limits K and L, but

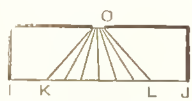

Fig. 145.

that beyond these limits no light reaches the paper through the aperture A.

Upon reflexion and refraction the light does **not** swerve at all **to one side**; AO and ON (Fig. 143), must in any case be in one plane, and then OB is in the same plane, which is called the **plane of incidence**; and OC is also in that plane. The Plane of Incidence is at **right angles** to the reflecting **surface**.

There is always one **particular angle of incidence** at which the Reflected and the Refracted rays are, or tend to be, at **right angles** to one another. For example, if the ratio of the velocities in the successive media be 3 to 4, as in air and crown glass, this angle of incidence is 53° 8′.

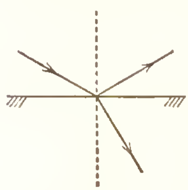

Fig. 146.

This angle presents some well-marked peculiarities. At that angle **no vibration** of the Ether which is effected **in the plane of incidence** can be **reflected** at all; and the whole of such a vibration is refracted into the glass. If we reflect common light from glass at this angle, all the components of vibration in the plane of incidence enter the glass; and the vibrations in the **reflected** ray are restricted (or rather, are approximately restricted) to oscillation at **right angles** to the **plane of incidence**. The ray reflected at this angle is therefore **plane polarised**; and reflexion from black glass at the appropriate angle of incidence, the so-called **Angle of Polarisation**, is one of the means of obtaining Plane Polarised Light.

The nearer the actual angle of incidence is to this angle of polarisation, the greater is the proportion of the incident light which is cut out in this way: so that all light reflected from clear glass, water, etc. is **partially polarised**, to an extent which varies with the angle of incidence or of reflexion. The refracted ray is partially polarised to an opposite extent.

Turn back to Fig. 144: suppose the course of the rays to be **reversed**. Let light come from $C_{,,}$ in the denser medium; it will be refracted towards $A_{,,}$. If it come from $C_{,}$ it will be refracted towards $A_{,}$, very nearly parallel to the surface of the glass. But let it come from some point between $C_{,}$ and H: there is no direction left in which it can be refracted at all: it is **not refracted** at all: it is **wholly reflected** within the glass, and the surface of the rarer medium is as effective a reflector as a metallic mirror would have been.

By reason of this "**Total Reflexion,**" a tumbler of **clear water** held above the head gives a clear mirror-image of objects on the table below it; a **bubble** of air in water, or a **test-tube** containing air immersed **in water**, will, when looked at under a certain angle, appear to have as bright a mirror-surface as that of mercury. If AB, Fig. 147, be a **glass rod**, opposite the extremity of which a lamp-flame is adjusted, the light entering at the face A is mostly totally reflected along the rod, and that repeatedly. At length it reaches the end-face B, which appears very bright. Even though the rod be moderately bent it may transmit light in the same way: and a contrivance of this kind is used by surgeons and microscopists in order to transmit light. If the rod be silvered externally, there is no light lost laterally: but if it be not, there is always a slight **lateral loss** along the length of the rod; and this lateral loss, which is greater when the outline of the rod is irregular, is utilised in "**illuminated fountains,**" wherein vertically ascending columns of water are illuminated from below, and act after the manner of the glass rod of Fig. 147; the column of water loses light all the way up, and that loss of light makes the column appear self-luminous.

Fig. 147.

A **total-reflexion prism** is sometimes used instead of a mirror in order to reflect light, say at right angles. In that case (Fig. 148), the face AB must lie at an angle of 45°; and in any case, the faces AC and CB must be so cut that the light shall enter and leave them **directly**, without any inclination; else there will be refraction, and different Colours will be produced, as in the prism. In **dissecting microscopes**, a total-reflexion prism is sometimes used to send a horizontal beam of light vertically downwards.

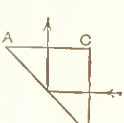

Fig. 148.

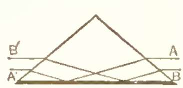

Fig. 149.

In a **reversing prism** light is refracted on entering, then totally reflected, and finally refracted into its original direction: but on looking through such a prism at an object AB, we see it upside down. Figure 149 explains this.

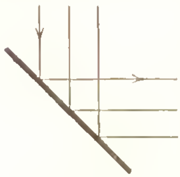
Fig. 150.

Plane Mirrors.—If a parallel beam of light, descending vertically, encounter a plane mirror at 45°, it will be reflected horizontally, as in Fig. 150. This explains the use of mirrors adjusted **outside windows** in narrow passages, to reflect into the apartment the narrow strip of **sky** light available.

A mirror at 45°, with a **central aperture**, is sometimes inserted in the body of a **microscope**, so as to send light from a lamp, placed to one side, vertically downwards, and thus to **illuminate the object**. The **cavities of the body** may sometimes be illuminated in the same way (**endoscopes**). The **eye** looks through the central aperture in the inclined mirror.

In Fig. 151, AB is the plane **substage mirror** of a **microscope**: the light which reaches any given point P of the object, from an **open sky**, is the same as if the mirror had been an **aperture** through which an open sky, below the mirror AB, illuminated the point P. The light which reaches P is limited by the **cone** APB. As we turn the mirror this cone diminishes or increases; but if we keep the **cone constant** by restricting the apparent visible area of the mirror by means of a **diaphragm**, it does not matter at what angle the plane mirror stands. If, on the other hand, the available light be itself **limited**, as by a distant window, CD, the cone of rays which reaches P is narrower, and any one such point as P is only illuminated by a **portion** of the plane **mirror**. If the point P had itself been the source of light, it is only that same limited area of the mirror which would have reflected light out through the window CD. The figure shows how limited the portion of the sky is whose light is turned to account in illuminating the point P, by means of a plane mirror, when the daylight has to come in through a window.

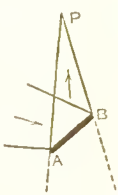

Fig. 151.

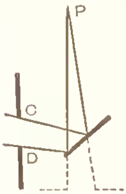

Fig. 152.

When light from a point O strikes a plane mirror surface, it is reflected so that after reflexion it *seems* to diverge from a point I behind the mirror, the same distance behind the mirror that O is in front of it (compare Fig. 52). If we trace out a few rays from O and draw the corresponding reflected rays, with the angle of reflexion equal for each to the corresponding angle of incidence, we find that the reflected rays will all, on being continued backwards, cross one another at the point I: and I is the **virtual image** of the point O. The word "virtual" implies that the reflected rays do not actually come from I, but that their course is, after reflexion, the same *as if* they had come from I.

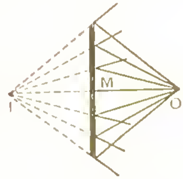

Fig. 153.

When the source of light is an **extended object**, light radiates from every point of it; and as a virtual image is formed for every point of it, we have a **virtual image** produced of the **object** itself.

Let AB (Fig. 154) be such an object, and let BD be a plane reflecting surface. The observer's eye is at F. Rays from A, reflected at E, enter the observer's eye at F; but then they seem to the observer to have come from A′. So for every point in AB. Let AB be a **cliff** and BD be smooth water; then the cliff AB is reflected upside down in the water. Again, let AB (Fig. 155) be a **cloud**, and CD be smooth water as before: the observer at F, looking at the water, sees the image of clouds inverted in form, and at an apparent **depth** below the surface equal to the real height of the clouds above it. If a person look at **himself** in a mirror opposite the **upper** part of his body he can see the whole of his own figure; for if AB (Fig. 156) represent his own figure, the rays from his feet B are reflected by the mirror and appear to come from B′. A person does not see **his own face** in a single mirror as other persons see it: what he sees as the

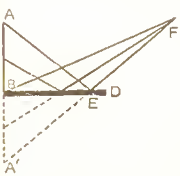

Fig. 154.

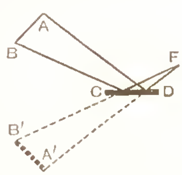

Fig. 155.

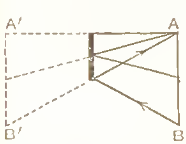

Fig. 156.

right side of his own image other people see as his left side. In order to see himself as others see him, he must use two mirrors.

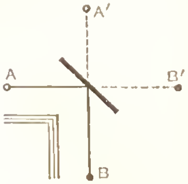

Fig. 157.

If one person look at another in a mirror, and not directly, if the person looked at look at the image of the observer in the mirror, it will seem to him that the **observer's image** is looking directly at him. In no case can one person look at another in a mirror without the mirror's being in a position wherein the person observed could in turn look at the observer in the mirror: **object** and **observer** are always **interchangeable**, as in Fig. 157, A sees B as if at B′; B sees A as if at A′.

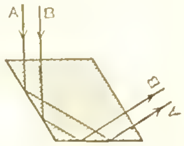

Fig. 158.

A transparent mirror, at 45°, is sometimes used in **scenic illusions**: a brightly illuminated object, out of sight of the audience, is reflected in the glass and appears as if it were on the stage.

In the **chemical microscope** the under surface of the object is looked at, and the rays from it are *twice* reflected by a **total-reflexion prism** so that they assume a direction more convenient for the observer (Fig. 158).

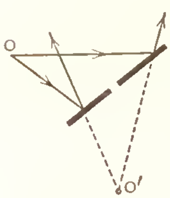

Fig. 159.

If a **small aperture** be made in a mirror, which mirror makes rays from O appear, after reflexion, as if they had come from O′, a piece of printed paper or any other **object** may be brought up to the same point O′; and then the **reflected image** of O and the actual **object** at O′ will, on our looking through the small aperture, seem to **coincide**; for the one **seems** as if it were at O′, while the other **really is** there.

In **Lionel Beale's camera lucida** the mirror is a piece of tinted glass; the object O is the virtual image produced by a microscope held horizontal: rays emerging are reflected upwards as if from O′; and at O′ is a sheet of drawing paper. The eye looking vertically downwards sees the image as if at O′; it also sees the drawing paper at O′; and with a pencil the outlines of the object may be traced upon the paper. The object should be brightly illuminated, and the paper not too bright.

In **Soemmering's camera lucida** a similar purpose is served by a minute mirror, smaller than the pupil of the eye: the centre of the pupil sees the reflected image, its rim sees the paper, both at O′.

In other forms of camera lucida the reflecting mirror-surface is that of a **total-reflexion prism**; and if in such a prism the light have to undergo **two reflexions**, there is **no inversion** of the image. In **Wollaston's** there is a two-reflexion prism, and half the pupil sees the reflected image, while the other half sees the paper and pencil directly.

The image of an object in a plane mirror can never be brighter than the object itself.

Rays reflected by one mirror may be re-reflected by another; and this may, if the mirrors be suitably arranged, be repeated so that **multiple images** are formed. We see this when two mirrors face one another at opposite sides of a room: the room seems to lengthen into a long vista.

If we look along a groove made up with two slips of mirror, we find that there is a series of multiple images of any object situated within the groove; and these images are symmetrically disposed in a circle, round a centre which coincides with the bottom of the groove. If the angle of the groove be an aliquot part of 360°, say 60° or 45°, the images are symmetrically arranged round this centre, and successive groups of images coincide with one another. This is applied in the **kaleidoscope**.

When a mirror is **rotated** through a given Angle, the **reflected beam** of light from an object is whirled through **twice** that angle: and to the eye at a fixed point the virtual image behind the mirror seems to **travel across** the mirror.

A **spot of light** looked at in a rapidly-rotating mirror has its image spread out into a **band**; for the successive positions in which the image is apparently seen are blended into one continuous impression by the "**persistence of images**" in the retina, which persistence endures for about one-sixth of a second.

Concave Mirrors.—If a mirror be spherical and concave, a flat wave-front, travelling towards it as if from an indefinitely distant source, is made to converge, approximately, upon a point called the **principal focus** of the mirror. After passing through this point, the wave-front opens out, and the rays diverge as if they had originated in the point F, half-way between the mirror and its centre of curvature C. The point F is therefore an image of the very distant source of light; and it is a **Real Image**, because the rays **really** do **pass through** F.

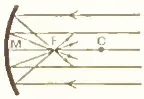

Fig. 160.

In order, however, that they should do this exactly, so that the focus F is truly a mere point, the reflecting mirror should be not spherical but **parabolic**, as in Fig. 54.

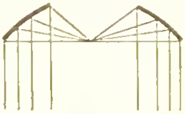

Fig. 161.

In **microscopic** work a ring-shaped **parabolic mirror** is sometimes used, suspended above the opaque object to be illuminated, and a parallel beam of light is sent vertically upwards. In other cases a **paraboloid** of **glass** is used, and sends rays to its focus by **total reflexion**: the glass is hollowed out at its summit, to admit the object to be illuminated.

If the source of light come nearer the mirror, that is, if it be at **any definite distance beyond** C, the Real Image is **nearer** the point C; when the source is near C, the real image is very near C; when it is **at** C, the real image is also **at** C, that is, the light is reflected by the mirror back to its source; when the source comes between C and F, the **real image** is **beyond** C, farther away from the mirror: when the source is at the **principal focus** F, the reflected wave-front is (approximately) **plane**, and the image is infinitely distant. When the source comes **between** the principal **focus** F and the **mirror**, the light diverges after reflexion *as if* it had come from a **Virtual Image** behind the mirror.

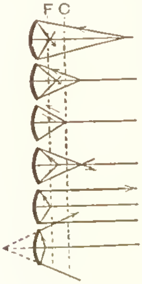

Fig. 162.

All this information is summarised in the **formula**

$1/d + 1/d' = 2/r$, where d is the distance of the source of light from the concave mirror, d' is the distance of the image, and r is the radius of curvature of the mirror.

Examples.—(1) Let the concave mirror have a radius of curvature equal to 10 cm.: let the object be at a distance of say 100 cm.; where will the image be? In the formula, $d = 100$, and $r = 10$: whence $\frac{1}{100} + \frac{1}{d'} = \frac{2}{10}$: and on working this out we find that $d = \frac{100}{19}$ or $5\frac{5}{19}$, so that the image is $5\frac{5}{19}$ cm. in front of the mirror.

(2) If the object be at 6 cm. from the mirror, where is the image? Here $r = 10$, $d = 6$; $\frac{1}{6} + \frac{1}{d'} = \frac{2}{10}$: whence $d' = 30$; and the image is at a distance of 30 cm., farther out than the object.

(3) If the object be at 4 cm. from the mirror, where is the image? Here $r = 10$, $d = 4$; $\frac{1}{4} + \frac{1}{d'} = \frac{2}{10}$: whence $d' = -20$: that is to say, the image is at a *minus* distance of 20 cm.; it is 20 cm. *behind* the mirror, and is therefore a Virtual Image, as in Fig. 162.

Pairs of points at the respective distances d and d', as defined by this formula, are called pairs of **Conjugate Points.**

Next suppose that the source (still considered as a point) is not at A in a line joining C, the centre of curvature, with the mid-point M of the mirror, but is **off the axis** MA, at a point B, still at the same distance from C as A had been. For such a point F′ acts as a Principal Focus; and if the point A′ be conjugate to A, B′ will be conjugate to B.

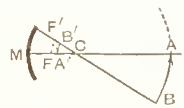

Fig. 163.

Similarly, if BA be a **curved object** whose centre of curvature is at C, every point in it will produce a corresponding **real image** of a **curved** form, also with its centre of curvature at C. The whole object AB will therefore produce a small real and **inverted** image A′B′. Conversely, if A′B′ be the object, the image will be at AB, also real and inverted, but this time **larger** than the object.

The relative Distances of the object and the image from the surface of the mirror, along the axis MFCA, remain determined by the formula given above.

If the object AB be straightened out, the inverted image is also straightened out, but not completely: it remains somewhat curved. If A′B′ be the object and be straightened out, the image AB is somewhat curved backwards. It is only in the central part of the image of a flat object that the image is approximately flat; hence the formulæ above apply to images and objects only when the breadth of the object or of the image is small, that is when the angle ACB or A′CB′ remains comparatively small.

Let the student bring his own face nearer and nearer to a concave mirror. At a distance he sees an inverted picture of his own face. What he then sees is the little inverted and slightly distorted real image A′B′ of his own face AB, in space between the principal focus F and the centre C, and therefore between himself and the mirror. As he approaches the mirror, the real image approaches him and looms larger and larger, because the angle under which it presents itself to his eye goes on increasing. As he comes still nearer, the real image is too near his eye for him to see it distinctly without strain; and then it is so near his eye that he cannot see it at all distinctly, though he sees that it is there. When his eye comes forward to C, the centre of curvature of the mirror, the image coincides with his eye and of course he can see nothing. As his eye still moves forward, the image is formed (or rather would be formed but for the obstruction offered by his head) behind his head, at a distance increasing to infinity as he moves forward: and of course during this stage he sees nothing. When his eye has moved forward to the principal focus and beyond it, the image of his eye is now virtual and erect, and behind the mirror, so that the observer may now, if the image be not formed too near his eye, see the image of his own eye reflected in the mirror. As he still approaches the mirror, the image of his eye rapidly approaches him; and it may then come too near for him to see it distinctly.

The relative sizes of the image and object are always proportional to their respective distances from the centre of curvature of the mirror.

Concave mirrors are used for making parallel rays, or rays divergent from a lamp, converge upon a small spot, which is then brightly illuminated; or again, for making divergent rays parallel. When a concave mirror is used for illumination, it is sometimes convenient to have a **small hole** at its centre, through which the eye may look at the object illuminated.

In the **Laryngoscope**, a **concave mirror**, attached to the forehead, concentrates light from a lamp upon a little **plane mirror** held at an angle of about 45° in the back of the mouth. This light is reflected downwards, and illuminates the larynx and windpipe. These act as illuminated bodies, and send light in all directions, so far as they can; that which strikes the little plane mirror is reflected horizontally through the open mouth, and reaches the eye of the observer through a small hole in the concave mirror. The virtual image of the larynx formed by the little plane mirror is correct as regards right and left, but is inverted.

When a **substage concave mirror** is used to illuminate an object under the **microscope**, the effect is, under an **open sky**, precisely **the same**—the same cone of rays reaches any given point of the object—as when a **plane mirror**, *with a rim of the same size*, is used. With a **limited source of light**, however, such as a window, the state of matters is different. In Fig. 164, P is a point of the object to be illuminated; but let us assume that point to be itself a source of light, and see under what conditions light would pass from it to the window. If P be a source of light, light spreading from it meets the mirror and is made to converge so as to make at P′ an image of the point P. Then this image radiates through DE so as, as it were, to illuminate a large area of the sky. Now reverse the course of the light. Light from a **comparatively large** area of the **sky** shines upon the point P′; the cone of rays is continued through P′, is reflected by the mirror, and illuminates the point P. The thin dotted lines show the cone of skylight obtainable from a plane mirror with the same rim. Hence the use of concave mirrors for producing brighter illumination in microscopic work; but in **daylight work** they have this effect only in rooms lit by **windows**; not under the open sky or close to a window fully open to the sky. On the other hand, suppose P′ in Fig. 164 is itself a source of light, say a **lamp**, the window being dark; the **concave mirror** will make an image of P′ at P; that is, it will **concentrate** light upon the particle P so as to make it, as it were, self-luminous. A **plane mirror**, on the other hand, would **disperse** the light coming from P′, for it simply reflects the ever-widening wave-

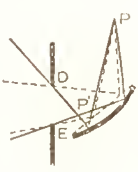

Fig. 164.

front; and the particle P would not be particularly well lighted up by such a mirror, used with a lamp.

In many cases, for examining the cavities of the human body, **specula** are employed. These are more or less conical tubes, whose inner surface is of bright polished metal. Light entering them is repeatedly reflected, and if they be conical it is concentrated, so that the fundus of the cavity is illuminated. If there be an aperture in their walls, the part of the wall of the cavity which corresponds to that aperture is illuminated.

Convex Mirrors.—If the mirror be convex, the rays from any actual source are **always** made to diverge so that they travel, approximately, *as if* from a **Virtual Image behind** the mirror. If the wave be plane fronted and the rays parallel, they appear after reflexion as if they come from the **principal focus** F, again half-way between the mirror and the centre of curvature C. When this source of light is nearer than an infinite distance, the virtual image is always somewhere between F and the mirror, as in Fig. 166. The **formula** which states the relations is this time $1/d + 1/d' = -2/r$.

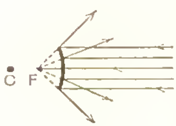

Fig. 165.

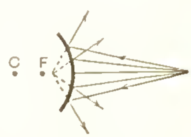

Fig. 166.

Examples.—(1) Let the radius of curvature be as before 10 cm., and the distance of the object 100 cm.; then $d=100$ and $r=10$; by the formula, $\frac{1}{100}+\frac{1}{d'}=-\frac{2}{10}$; whence $d'=-\frac{100}{21}$ $=-4\frac{16}{21}$; or the image is $4\frac{16}{21}$ cm. *behind* the mirror, and is therefore virtual, as in Fig. 166.

(2) If the distance of the object be 4 cm., we have $\frac{1}{4}+\frac{1}{d'}=-\frac{2}{10}$; whence $d=-\frac{40}{18}=-2\frac{2}{9}$; and the image is $2\frac{2}{9}$ cm. behind the mirror, and is again virtual.

Convex mirrors form **virtual images** of **extended objects**, which are **erect** and always **smaller** than the object.

With a convex mirror a person always sees an erect small image of himself.

On a small **drop of mercury** there is a minute reflected picture of surrounding objects, which is a severe test for a microscope.

The **image** of a straight or plane object is **curved** in the same sense as the convex surface itself.

From the **position** and **size** of the **reflected images** of a known object, such as a scale, we may calculate the **radius of curvature** of the mirror; and for the smooth reflecting surfaces of the Eye, this is effected by means of the **Ophthalmometer.**

Refraction.—Let us put a penny in a basin and stand so that the penny is just out of sight: if the basin be then filled with water the penny **comes into view.** Fig. 167 explains how this is: the rays from the penny are refracted upon emerging, and the coin is then visible to the eye at E. A **stick** appears **bent** when one-half of it is immersed in water; any given point of it *appears* higher up in the water than it really is.

Fig. 167.

For this reason also we underestimate the **depth** of **water**; and if we look down at the table-cloth through a clear tumbler of water, the table-cloth seems to stand at a higher level under the water. The **sun** is still visible when it has astronomically "**set**" for some time: if S be the distant sun, really below the horizon, the rays from it are bent by the atmosphere so that they **appear** to come from S′; and the same cause disturbs the apparent position of every **star** in the heavens, except one which might happen to be vertically overhead at any given moment.

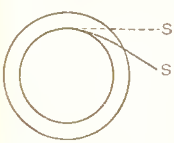

Fig. 168.

Light-waves of **different frequencies,** or Colours, are **unequally refrangible.**

We have already seen this in the production of a **spectrum** by a Prism.

If white light radiate from a particle S under water, on its emerging into the air the red is least refracted and the violet most so, while the intermediate colours of the spectrum are refracted to intermediate extents (Fig. 169).

Conversely, if light travel from a particle in the air, on its entering water the waves corresponding to the different colours are again differently refracted, the red least so, the violet most so (Fig. 170). The **red** colour-waves are thus the **least refrangible**, the **violet** the **most refrangible**, among the radiations which give rise to the sensation of sight. This indicates that while in the Ether all the waves travel with the same speed, in our ordinary transparent substances the **red** waves travel **most slowly**, the violet most rapidly.

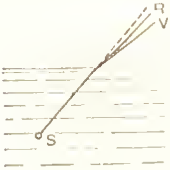

Fig. 169.

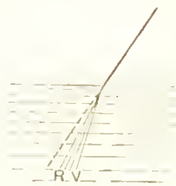

Fig. 170.

A **stick** immersed in water seems **blue** on one side, **red** on the other; and such colours are often beautifully seen in aquaria and rock-pools.

If white or mixed light, from a **single point**, were to enter a slab of glass of some thickness through an extremely minute aperture, it would be refracted, the violet most, the red least; and **on emerging**, all the rays would travel **parallel** to their original course. But they would have **separated** from one another to some extent during their passage through the glass: and if in Fig. 171 a screen were placed at RV, the spot of light received on it would not be white, but would form a Spectrum. If the source of light be an **extended source**, the extended spot of light formed on the screen will correspond to the overlapping of a number of spots such as that indicated in Fig. 171; and this overlapping would result in **white** light everywhere except at the **edges** of the beam, one side of which would present uncompensated **red**, the other uncom-

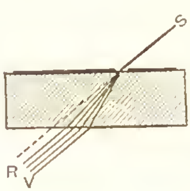

Fig. 171.

pensated **violet**. The **margins of the spot** on the screen will therefore be **coloured**.

If the sides of the slab be not parallel, the light as a whole will not resume its original direction, but will undergo "**deviation**"; and the different colours will be differently deviated, so that they will be "**dispersed**" from one another: and a screen, at a sufficiently great distance, will receive, instead of a coloured spot, a coloured band of light, for the red and the violet will, before reaching the screen, have diverged or been dispersed materially from one another.

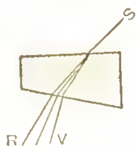

Fig. 172.


Fig. 173.

This is applied in the **Prism**, a rod of glass or quartz, of triangular section, usually equilateral or right-angled (Fig. 173).

If a beam of white light be allowed to fall upon one face of the prism, the different colours are deviated and dispersed as shown in Fig. 174; and a screen suitably placed will receive the **Spectrum** produced.

Fig. 174.

If we confine our attention to **one colour** at a time, we find that the rays from a source S may come very nearly to a **focus** and form a **Real Image** at a point S′; that this occurs when the **angle of emergence**, i', for the particular colour, is **equal** to the **angle of incidence**, i; and that this only occurs when the **Angle of Deviation** is a **minimum**. That is to say, if we rotate the prism back-and-fore round its own axis, we find that there is a particular position of the prism in which the point S′ is higher up in the figure than in any other: and that the image of S formed at S′ is then the sharpest possible. It is not possible, therefore, to have all parts of the spectrum sharply in focus at the same time: this position of

Fig. 175.

Minimum Deviation must be found for **each colour** in succession, by turning the prism.

When we have found this position for the prism, we may then measure the **angle of incidence**, i, of the beam of light upon the prism, Fig. 175; we should already know the **angle A of the prism**; and then we are in a position to find the **Refractive Index** β of the glass of the prism, for the particular kind of light which is then under observation, by means of the formula $\beta = \sin i \div \sin \frac{1}{2} A$. If the angle of the prism be 60°, this becomes $\beta = 2 \sin i$; if 45°, it is $\beta = \sin i \div 0{\cdot}728$.

The Index of Refraction may also be found by measuring the angle of incidence at which **total reflexion begins** to occur; for then β is equal to the sine of that angle.

Sometimes a **hollow prism** is used, of glass, filled with bisulphide of carbon. When the prism is, for any colour, in the position of minimum deviation, the whole of the refraction for that colour is due to the bisulphide, none to the glass itself: for were it not for the bisulphide, the rays would emerge parallel to their original course, provided that the walls of the hollow prism were themselves of parallel-faced glass.

The source S should be made as **narrow** as possible, so that there may be as **little overlapping** as possible in the resultant Spectrum, and that each colour may accordingly be as **pure** as possible. This might be effected by using, as the source of light, a straight wire heated to incandescence by an electric current. More usually it is effected by a "collimating" arrangement, Fig. 176. A is a screen in which there is a narrow **slit**, widened out in the figure for the sake of clearness; behind this there is a **lamp** S. The **lens** L catches some of the rays which traverse the slit A; and if the **slit** be at the **focus** of the lens, the lens will make those rays **parallel**: such a lens is said to be a collimating lens, or a **collimator**. The waves are then plane fronted on their way towards the prism. After emergence from the prism, the rays are received in a kind of opera glass or **telescope** by which they are, for each colour successively, brought to a focus on the retina of the eye. The eye then

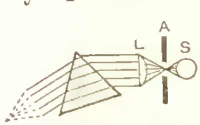

Fig. 176.

receives, for each colour, an image of the narrow slit. This combination is a **Spectroscope**; and in the path of the rays between the collimating lens L and the prism we may insert solutions, etc., whose **absorption-spectra** we wish to study. When we wish to study the **emission-spectra** of different flames, we put these at S.

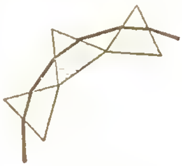

Fig. 177.

In most spectroscopes there are **several prisms**; by this device the total amount of deviation and dispersion is increased and the spectrum is lengthened out. In some cases the number of prisms is halved: if for instance we use a **half-prism** with its face B **silvered**, the refracted rays are turned back when they reach the silvered face, and come out at the same face by which they entered, dispersed to exactly the same extent as if they had traversed the entire prism. Some very convenient forms of spectroscope are made on this principle.

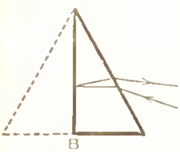

Fig. 178.

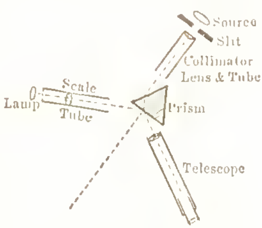

Fig. 179.

In almost every table spectroscope there will be found a third tube, a "**scale tube**," with a lamp. This tube bears a **graduated scale** and a **lens**, the mutual distance of which can be adjusted so as to make the rays from the scale parallel. These rays are then reflected from the face of the prism into the telescope tube, and the image of the scale can be seen in the telescope, along with the spectrum itself.

To use a spectroscope: (1) **focus** the **telescope** on a very **distant** object, and thus adapt it for receiving parallel rays; put it in its place in the instrument; (2) remove the prism and move the slit, or the collimator-lens, until the **telescope**, directed down the collimator-tube, can show the **slit distinctly**; the slit is then in the focus of the collimator-lens; (3) put the prism in place, and adjust it for **minimum deviation**; that is, turn it into a position in which the selected colour is in the middle of the field of view of the telescope with the telescope as nearly as possible in a straight line with the collimator-tube: (4) turn the **scale-tube** until its light enters the telescope, and then adjust the scale and lens until the **scale** is **distinctly**

seen in the telescope; (5) see that the virtual images of the slit and of the scale coincide, by moving the eye from side to side; there ought to be no relative movement between the scale and the spectrum; if there be, carefully adjust the scale or its lens.

If we combine **two prisms** of the same glass and the same angle, as in Fig. 180, the two prisms together act like a slab of glass; there is then **no** resultant **deviation** and **no** proper **dispersion**; a beam of light emerges coloured only at its edges. If, however, we combine a prism of **crown-glass** and one of **flint-glass**, though we may adjust the angles of these so that there is **no deviation**, we find that there still is **dispersion**, and a **spectrum** is formed.

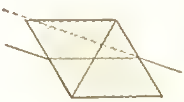

Fig. 180.

Such prisms are usually connected by **Canada balsam**, which has a refractive index intermediate between that of flint and that of crown, and therefore minimises the loss of light by reflexion at the junction.

This result, dispersion without deviation, is rather curious. It depends on what is called the "**Irrationality of Dispersion**"; which is, that in different transparent substances the Deviation and the Dispersion are independent of one another; that is to say, the **deviation** of any given Colour depends on the **refractive index** for that colour, and the **dispersion** depends on the **differences between** the **refractive indices** for the successive colours. The refractive indices may on the whole be small in any particular substance, and yet the differences between them may be great, or *vice versâ.* Therefore to neutralise deviation is not necessarily to neutralise dispersion. But when we are able to neutralise deviation without neutralising dispersion we are able to make a convenient form of **spectroscope** in which there is a **straight train** of **prisms**, as in Fig. 181. In this instrument, the **Direct Vision Spectroscope**, there is a chain of alternating crown and flint glass prisms: the light is admitted by a slit at A; it comes through to the lens L: the eye looking through the lens sees a spectrum situated at the image of the slit: and the lens can be adjusted so as to bring each colour successively into focus, by focussing each successive local coloured image of the slit.

Fig. 181.

Such trains of prisms are employed in the **spectroscopic eye-pieces** of **microscopes**, which produce a short spectrum in which absorption-bands are identified with comparative ease. These eye-pieces are often provided with a **total-reflexion prism** for reflecting, from one side, a **comparison-spectrum** in such a way as to occupy half the field of view.

By properly shaped prisms of suitable material, we can obtain **deviation without chromatic dispersion**. If we take a flint-glass prism which will produce on a given screen a spectrum which is say 3 inches long between two definite colours; and a crown-glass prism which will do the same thing: and if then we set these two prisms in the path of the beam of light so as to neutralise one another's chromatically dispersive effects, the incident beam of white light will come through recombined and white: but it will (therein differing from Fig. 180) have been **deviated** from its original direction. The second prism has neutralised the dispersive action of the first and has only partially, not completely, neutralised its deviating action. One prism may therefore be **achromatised** by another; and the pair of prisms, acting together, form an Achromatic Prism, a prism which produces deviation without producing colour-dispersion, just as a mirror does.

Lenses

If we examine a collection of lenses, such as spectacle-glasses, we find that some of them are thicker in the centre than at the edges, while some are thicker at the edges than at the centre. Let us call these respectively **thin-edged** and **thick-edged** Lenses.

If we take up a thin-edged lens, we see that we can make it act as a **magnifying-glass**, as for example when we examine the skin of the hand with it; and that if we hold it up between the Sun and a piece of white paper we can make it act, more or less efficiently, as a **burning-glass**, for it produces a small image of the sun on the paper if the paper be held at a suitable distance from it.

When a thin-edged lens is used as a magnifying-glass to examine the skin of the hand, an image of the skin is seen enlarged in size; but, though we would certainly not expect this, that **image** seems to be **farther away** than the skin. The Eye has, when the magnified image is being looked at, to adjust itself as if it were looking at a more remote object.

Thin-edged lenses differ from one another in respect of the **distance** at which they can produce an **image of the Sun**: and it will be found that the lenses which are on the whole **flattest** in form will produce such an image when they are held at the **greatest distances** from the paper; while those which tend most nearly towards a globular form will form such images at the shortest distances. Each thin-edged lens has therefore its own proper distance at which it will form such an image of the Sun (or more properly, of an indefinitely distant object); and this distance is called the **Focal Distance** of the thin-edged lens in question.

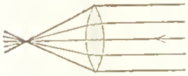

Fig. 182.

Thin-edged Lenses are **convergent** lenses; that is, they make rays of light converge; they bend them towards the axis of the lens, towards the thicker part of the lens, just as a prism does towards its own thicker part (Fig. 182).

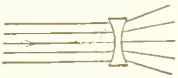

Fig. 183.

Thick-edged Lenses cause light to diverge from the axis and are hence called **divergent** Lenses; but these also bend the light towards the thicker part of the lens, that is, in this case, towards the periphery (Fig. 183).

These thick-edged lenses act as **diminishing-glasses.** If a landscape be looked at through such a lens, the landscape is seen diminished; but the curious phenomenon is presented that, quite contrary to the impression at first received, the **diminished** picture or **image** of the landscape seems to be **much nearer** the eye than the objects in the landscape themselves are: in fact it is mostly some few inches only from the lens. When such a lens is held up to view a landscape, and when the landscape itself and the diminished image are alternately looked at, with one eye, this will be felt to be true; for the effort which the Eye makes in order to see the diminished image clearly, is the same as that which it makes in order to see a near object distinctly.

We can obtain a **diminished** view of the landscape even with a thin-edged lens: but in that case it is an **inverted** one. Take any ordinary thin-edged spectacle-lens and hold it at arm's length between the eye and the window; an inverted image will be seen, small in size. Where is that image? It is as if there were a little transparent picture of the window and landscape, hung up in the air between the observer and the lens. In order to see this suspended image, we must be able to get far enough behind the lens to look at that suspended little picture as if it were itself an ordinary object of vision at that place. It is best to use one eye only. It will not do to bring the eye too near it, or to prevent the formation of that image by bringing the head too far forward; in the former case we cannot see it, because it is too near the eye; in the latter case the rays of light are prevented, by the interposition of the head, from forming the image at all. We can easily satisfy ourselves that this **real image**, as it is called, is formed in the air between us and the lens, by moving a bit of **tissue-**

paper or cigarette-paper back-and-fore between us and the lens. We shall find some position in which the little inverted picture is clearly defined on this improvised screen: and then we find, on slipping the paper screen out of the way, that we must focus the eye, if we want to see the image clearly, in exactly the same way as we had done when the paper was in its proper position. The natural tendency is, when we remove the paper, to do something of the nature of looking through the lens; but if we do this, we find that we do not see the image clearly. We must get our eye back to the same focussing as when we looked at the paper itself. A little paper screen is thus a convenient means of finding out where the real image is; and if it be wetted or oiled, all the better. But we may equally well find out where the real image is, by looking at the paper from the other side: and we shall have no difficulty in finding that the **real image** of a **nearer object** is **farther from** the **lens,** that of a **farther** object somewhat **nearer** to the lens; and that the image of the **Sun** is **nearest** of all to the lens.

If we take a **thick-edged** lens, and try to find out by the same means where it forms real images, we shall find that there is no such place: **no image** is formed on the **screen** at any distance on either side of the lens. It only seems to us, on **looking through** the lens, *as if* the image were at a certain distance on the other side of the lens.

A **Real Image,** when formed, is formed at a real and actual **crossing-point of rays.** Rays from any given point of the object looked at, as they diverge from that point, meet the thin-edged lens: the lens makes them converge, so that they sooner or later cross one another, the front of the wave from the point in question being then reduced to the smallest possible dimensions. But once they are through the crossing-point, they **diverge as if** they had **originated** in that point: and our eye sees the corresponding image or picture at the place where these crossing-points occur. A **thick-edged** lens, on the contrary, makes rays diverge: and if they are already diverging from any one point in a given object, it makes them **diverge** more sharply, *as if* they had come from a corresponding point in a **nearer object**; and thus they form an image which is not real, for it does not correspond to any real crossing-point of rays, but is **imaginary** or **virtual**.

Full treatment of the subject of Lenses leads to somewhat complicated **formulæ**, in which we have to consider among other things the **thickness** of the lens. But let us, in the first place, set this thickness out of view; that is, let us imagine our lenses to be reduced to **no appreciable thickness**, to **mere films**. Further, let us take note that there is a convention or agreement among physicists, that in speaking about lenses, they will assume the **source of light** to be somewhere to the **right**, so that its distance from the lens is Positive (distance to the left being reckoned as negative). It will make matters plainer if we adhere to this convention, at any rate in the first place.

Let us take a **convergent lens** which makes an image of the Sun at 30 cm. distance; that is, one which has a Focal Distance or Focal Length of 30 cm. We denote the Focal Length by the symbol f. Now draw a base-line, the **Optic Axis**, a line which passes right through the middle of the lens, at right angles to the lens. Then we draw a vertical dotted line to indicate the position of our ideally-thin convergent lens: and along the axial line we measure off a number of distances, each equal to f, the Focal Length of the lens. Thus the point A (Fig. 184) is at a distance $+2f$ from the lens, and the point B at a distance $-2f$.

Fig. 184.

Now let us assume a **wave-front**, travelling in the line of the axis AB, to be **converging** towards any point O, say at a distance from the lens equal to $-f$. It does not matter how it has been produced: we may, if we please, assume that another convergent lens has given it its convergence. The lens will make it converge upon and pass through a point IR, also upon the axis, at a distance $-\frac{1}{2}f$, or $\frac{1}{2}f$ to the left; in this case 15 cm. to the left; and a screen at 15 cm. to the left will show a **real image** of O.

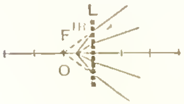

Fig. 185.

Next increase the distance between the lens and the point upon which the wave is converging: let this distance be say $-2f = -60$ cm.; then the rays are bent so that they converge upon IR, where the distance between IR and the lens is $-\frac{2}{3}f$, $= 20$ cm. to the left.

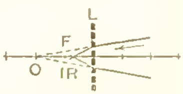

Fig. 186.

The farther O is carried away from the lens to the left, the more nearly does the corresponding point IR come up to the point F, situated at a distance f to the left of the lens; but it never quite comes up to that point until the point O is at an *infinite* distance—greater, that is, than any assignable number of inches or of miles. When that is the case, the incident wave-front is quite flat, and the rays are parallel. Fig. 187 illustrates this case. **Parallel incident rays are brought to a Focus at F.** The rays of the Sun may be and are taken as **practically** parallel, the Sun itself being so distant: and if the sun be to the Right, its image is formed at F, to the Left. F is called the **principal focus** of the lens; and physicists say that a Convergent Lens has a Negative Focal Length, because its Principal Focus is to the left.

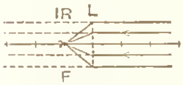

Fig. 187.

Ophthalmologists, on the other hand, speak of **convergent** lenses as having a **positive focus,** or a positive focal length.

In the next diagram, Fig. 188, the **wave-front** is a

divergent one: it comes from a point at a distance along the axis which is greater than $2f$, but less than infinity. It is made to converge upon and to traverse a point farther away from the lens than F is, but at a distance numerically less than $2f$ to the left.

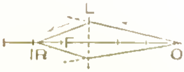

Fig. 188.

When, however, the source of light is at a distance $+2f$, the point of convergence, the crossing-point of rays, is at a distance $-2f$ (Fig. 189).

Fig. 189.

Again, so long as the source O is at a distance less than $2f$ but more than f to the right, the nearer O is to the lens L, the farther towards the left is the point IR thrown; until, when O is at a point at a distance f to the right, that is at a **principal focus,** IR has receded to an infinite distance, and the rays which have traversed the lens L have been rendered **parallel** by it (Fig. 190).

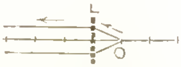

Fig. 190.

As the source O comes **still nearer** to the lens L, we find that although the lens is convergent, it cannot altogether do away with the divergence of the rays from O; it only succeeds in rendering them **less divergent** than before; and after refraction by the lens, the course of the rays is *as if* they had come from a **source more remote** from the lens. Figs. 191 and 192 illustrate this. In Fig. 191 O is at a distance say equal to $\frac{2}{3}f$ from the lens, and the rays then travel *as if* they had proceeded from a Virtual Image IV at a distance equal to $2f$ from the lens; positive, to the right.

Fig. 191.

In Fig. 192, O is at a distance $\frac{1}{2}f$, and in that case IV is at a distance equal to f. As O approaches the lens, therefore, the virtual image at IV rapidly gains upon it; and in order to get the greatest possible distance between O and IV, the source O must

Fig. 192.

stand at a distance from the lens as nearly as possible equal to f, but at the same time distinctly less than f.

It will be seen that this series of diagrams is **symmetrical**; that the first resembles the last in form, though it is reversed in direction; and so on. But the series of figures may also be used to tell us what will occur if we give the source O a corresponding series of positions to the left of the lens L. If we put O in the position of IR, we always find that IR occupies the previous position of O: the **Object** and the corresponding **Real Image** are **interchangeable.**

All this information, and a good deal more, as to the relative positions of object and image along the axis, is contained within the **formula** $1/d' = 1/d + 1/f$, where d means the distance of the object at O from the lens, d' the distance of the image, and f the focal length, all in inches, or all in cms. But in applying this formula to any numerical problem, we must not forget that in a Convergent Lens f has always a **negative** numerical value.

Numerical Examples.—(1) A convergent lens of 20 cm. focus ($f = -20$); the object O at an indefinite distance ($d = +\infty$): where is the image formed? $1/d' = 1/\infty - 1/20 = 0 - 1/20 = -1/20$; therefore $d' = -20$ cm.; a Real Image, 20 cm. beyond the lens.

(2) The same lens with the object O at 6 metres ($d = +600$ cm.); $1/d' = 1/600 - 1/20 = -29/600$; $d' = -600/29 = -20{\cdot}669$ cm.; I is at 20·669 cm. on the other side of the lens; a Real Image.

(3) The same lens with the object at 40 cm. distance ($d = +40$); $1/d' = 1/40 - 1/20 = -1/40$; $d' = -40$; a Real Image.

(4) The same lens, with the object at $12\frac{1}{2}$ cm. ($d = +12\frac{1}{2}$); $1/d' = 1/12{\cdot}5 - 1/20 = +15/500$; $d' = +500/15 = +33\frac{1}{3}$ cm.; in this case the Image is on the same side of the lens as the Object, and is **virtual.**

(5) The same lens, with light from the right **converging** on a point 10 cm. to the **left** (*i.e.* $d = -10$); $-1/10 - 1/20 = -3/20$; $d' = -\frac{20}{3} = -6\frac{2}{3}$; the light is made to **converge** upon a point **nearer to the lens.**

Let us now turn to the other class of Lenses, the

thick-edged or **divergent.** Their behaviour may be summarised in the same formula $1/d' = 1/d + 1/f$, in which f, the **focal length**, is now **positive**.

Numerical Examples.—(1) A divergent lens of 20 cm. focus ($f = +20$); the object O is at an infinite positive distance (*i.e.* parallel light from the right; $d = +\infty$); where is the image? Ans. $1/d' = 1/\infty + 1/20 = 0 + \frac{1}{20} = \frac{1}{20}$; $d' = 20$; 20 cm. to the right of the lens; a Virtual Image at the **Principal Focus.**

(2) The same lens with the object O at 6 metres ($d = +600$ cm.); $1/d' = 1/600 + 1/20 = 31/600$; $d' = 600/31 = +19{\cdot}355$; 19·355 cm. to the right of the lens; again a virtual image, a little nearer than the principal focus.

(3) The same lens, with the object at 6 metres to the left; that is, with light from the right **converging** on a point 6 metres beyond the lens; $d = -600$; $-1/600 + 1/20 = 29/600$; $d' = +600/29 = +20{\cdot}669$ cm. The **slightly convergent** rays have been made to **diverge** as if from a point to the right.

(4) The same with the object in the same way at 20 cm. to the left: $1/d' = -\frac{1}{20} + \frac{1}{20} = 0$; $\therefore d' = \infty$; the **convergent** rays have been made **parallel.**

(5) The same, with the object in the same way at 16 cm. to the left; $d = -16$; $1/d' = -\frac{1}{16} + \frac{1}{20} = -\frac{1}{16} + \frac{1}{20} = -\frac{1}{80}$; $d' = -80$; 80 cm. to the left: the **convergent** rays have been made to converge upon a **more remote** point.

In all this it is assumed, in accordance with the physicists' convention, that the **source** of light is to the **right.** Then a convergent lens has a negative focus (to the left) and a divergent one a positive (to the right). The practice of writers on Ophthalmology is, however, to consider the light as coming from the **left**; and then a convergent lens has a positive focus (to the right), and a divergent a negative (to the left). Some writers on Optics, too, do the same thing; and therefore the student has to be on his guard as to the sense in which terms are being used in any particular book or paper.

Closely connected with this is another divergence of modes of expression. The fraction $1/f$, which goes by the name of the **power of a lens,** is used by physicists as the measure of the **divergence** produced by that lens.

But it is convenient in many cases to take $1/f$ as a measure of the **convergence** produced by a lens. Then this would be positive in a convergent lens, negative in a divergent lens. But if that be so, then a **convergent** lens must be described as having a **positive** focal length f, and a divergent lens a negative. This is the point of view from which **ophthalmologists** have come to their present convention as to nomenclature. They have agreed (Internat. Ophthalm. Congress, 1875) to consider their **standard lens** as a **convergent** lens whose **focal length is one metre**. In such a lens the Convergent Power is $1/f = 1 \div 1$ metre $= 1$, unity, one **Dioptre**, or 1 D. In a convergent lens whose focal length is 5 cm. or 0·05 metre, the convergent power is $1/f = (1 \div 0{\cdot}05) = 20$D. A metre is taken as being practically 40 inches; so that a convergent lens of 8 inches focal length has a convergent power of $(1 \div \frac{8}{40}) = \frac{40}{8} = 5$ D.

Now it happens that when we combine two lenses, say of focal lengths f and f', then (on the express assumption that we continue to **neglect** the **thickness** of the lenses) the **Power** of the **combination** is the **sum of the powers** of the two (or more) lenses taken singly. If $1/F$ be the power of a combination of our two lenses, $1/F = 1/f + 1/f'$. Suppose we want a combination whose power shall be $1/F$, while we have a lens of focal length f; we must find another lens whose focal length is f' in order to make up the required combination.

It may be, with a convergent lens, that f is too great and our lens not sufficiently convergent. In that case we must combine a **convergent** lens with the **insufficiently convergent** one in order to bring about the desired result. Assume that we want to make parallel rays converge upon a point 30 cm. beyond the lens, and that one of our lenses makes them converge upon a point 40 cm. away. Then $F = 30$; $f = 40$; find f'. From the equation $1/30 = 1/40 + 1/f'$ we find $f' = 120$; and the focal length of the required additional convergent lens is 120 cm.

Again, if our lens be **too convergent**, we must combine a **divergent** lens with it. Assume that we want to make parallel rays converge as before ($F = 30$), and that our lens brings parallel rays to a focus at 20 cm. distance ($f = 20$); then we find from the equation that $f' = -60$; and we need a divergent lens of 60 cm. focal length. This divergent lens has the effect of throwing the **image farther off.**

The ophthalmologists' mode of effecting these computations would be the following. The **required** convergent power or **dioptry** is $3\frac{1}{3}$ D ($= 1 \div 0{\cdot}3$ metre); the first lens has a dioptry of $2\frac{1}{2}$ D ($= 1 \div 0{\cdot}4$ metre); we need an **additional** dioptry of $\frac{5}{6}$ D ($= 3\frac{1}{3} - 2\frac{1}{2}$); and the lens to be used must therefore be a **convergent** lens, and have a Focal Length of $\frac{6}{5}$ metres, or 120 cm. In the latter case the lens has a dioptry of 5 D ($= 1 \div 0{\cdot}2$): but we only need $3\frac{1}{3}$ D; therefore we must **reduce** the dioptry by a lens of $-1\frac{2}{3}$ D; that is, the lens to be employed is a **divergent** one, whose Focal Length is $-\frac{3}{5}$ metre, or -60 cm.

This is applied in the following manner. The **human eye** when perfectly normal (emmetropic) and at absolute rest, as when one meditatively contemplates space, brings **parallel** rays, or rays from an infinite distance, to a **focus** on the **retina** of the eye. Rays from **nearer objects**, under the same conditions, tend to be brought to a focus at points **behind** the retina, so that when they do impinge upon the retina they have not yet come to a focus; and they therefore, under these conditions, produce no clear image. But the Eye has itself a certain power of "**accommodation**," that is of altering the curvature of the Crystalline Lens and making it more convex. This is equivalent to our having at command a **series** of **convergent** lenses of all focal lengths from **infinity** down to the **least distance** of distinct vision. Take a young man of 20 years of age: he can usually see an object at 10 cm. from his eye, but not if it be nearer; the accommodation has, as it were, supplied him with a **lens** which, in conjunction with the **normal eye** accommodated for infinity (that is **not accommodated** at all), forms a **combination** able to bring the rays from the near object to focus upon the retina: the **divergent** rays from the near object, striking the accommodated eye, are then equivalent to parallel rays striking the unaccommodated eye from an infinitely distant object: and in the eye, behind the lens, they take a course the same as that which rays from an infinitely distant object would have taken had the eye remained unaccommodated; whence the virtual additional lens has an adjustable Convergent Power or Dioptry ranging all the way from 0 to 10 D. In short-sighted or myopic eyes, the convergence is naturally too rapid for the shape of the eye, and parallel rays come to a focus too soon, that is, in front of the retina. In such cases it will be found that there is a remote point of distinct vision, let us say at 50 cm. Rays from a point at 50 cm. distance are just able to come to focus upon the retina; rays from any farther point come to a focus too soon; so that the short-sighted Eye is itself practically equivalent to a normal eye *plus* a virtual convergent lens of focal length 50 cm. or dioptry 2 D. In order to enable such an eye to see remote objects, it must be restored to the condition of a normal eye. This is done by neutralising the virtual convergent lens by adding a divergent lens whose dioptry is -2 D; whence the use of divergent lenses by short-sighted persons. Of course, questions as to whether it is expedient to attempt to effect this neutralisation completely, and thus to throw work upon the ciliary muscle which it has not been accustomed to do, pertain to the domain of Ophthalmology and not to that of Physics. In long-sighted or hypermetropic persons, the eye is similarly equivalent to a normal eye *plus* a virtual divergent lens, so that the rays do not converge to a focus rapidly enough to suit the form of the eye; in that case the error must be corrected by the addition of a corresponding convergent lens. In the case of a long-sighted person, however, it will be noted that the error can to a great extent be compensated by making use of the Accommodation of the eye itself; and a person with a tendency to this defect naturally does this unconsciously: it is only when he is approaching the limits of exhaustion of his accommodation, which itself diminishes with advancing years, that he learns that he has been habitually using his accommodation so as to provide himself with a virtual lens, when he should have provided himself with an actual one. When a person is about 50 years of age, with a normal eye, he generally has about $2\frac{1}{2}$ D accommodation left; that is, his least distance for distinct vision is about 40 cm.; and if he wants to see objects at a less distance than this, he must use convergent spectacle-glasses of say 2 D or $2\frac{1}{2}$ D, so as to bring the combination of eye and lens up to a maximum convergent power of say 4·5 D, which will enable him to see objects at a distance of 22 cm., or of 5 D which will enable him to see them at a minimum distance of 20 cm., if he strain his accommodation to the utmost.

Thus we see that a pair of lenses may act like a single lens; and we have seen what the **formula** in general use is, whereby the Focal Length of a pair of lenses may be estimated. But this formula is only an **approximate** one, though used as above for practical purposes. It is implied in its use that not only are the two lenses in contact, but that neither of them has any thickness at all, so that both are mere **refracting films, coincident** in position. The exact formula is much more complicated than that given; but it does not appear to be necessary to trouble the student with it.

Non-axial Object and Image Points.—All that has been said applies to rays coming from or converging towards a point in the Axis of the lens, and converging towards or apparently diverging from some other point also in the Axis of the lens. Next, as to points not on the axis, the elementary theory, which gives rough **approximations** merely, approximations only applicable when the objects and images are of **no great breadth**, assumes that if we have two points, one axial and one non-axial, but both at equal axial distances LO and L′O′ from the lens, then their images are also at equal axial distances from the lens.

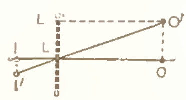

Fig. 193.

Then of the two points O, O′, the respective images are I, I′: and if OO′ be an object, the image of that object is II′.

If we make this assumption we may say that in any lens the distance d of the object, the distance d' of the image, and the distance f of the principal focus, all measured to the right, are stated by precisely the **same formulæ** as those which we have already given to show the relations between these distances when the objects and images were **axial points** merely. And by similar triangles, the **linear sizes** of the object and image are in all cases **proportional** to their respective **distances** from the lens, considered as a refracting film merely, so that the image may in many cases be larger than the object. Further, whenever the image and the object (real or virtual) are on **opposite** sides of the lens, the image is **inverted**; while when they are on the **same side** of the lens, it is **erect**. And an **object** is always **interchangeable** with its image, if the image be a **real image**; so that the **photographic camera** and the **magic lantern** or photographer's enlargement lantern are **converse cases**, the one making a small real image of a large and distant object, the other a large and distant real image of a small object near at hand. It will be borne in mind that **virtual images** are never formed upon a screen and are only to be **seen through the lens**, while **real images** may be seen either with the aid of a **screen** or by the unaided **eye** placed at a sufficient distance along the line of the rays.

To illustrate the **real images** formed by a convergent lens, we may take a **long-extension camera** with a short-focus single symmetrical lens say of $5\frac{1}{2}$ inches focus. For the horizon or very distant objects the ground-glass **screen** must be $5\frac{1}{2}$ inches from the centre of the lens: for objects at 100 yards it must be at 5·508 inches: for objects at 100 feet, at 5·525 inches; for 20 feet, at 5·629 inches; for 15 feet, at 5·673 inches; for 10 feet, at 5·764 inches; for 8 feet, 5·834 inches; for 6 feet, 5·956 inches; for 5 feet, 6·055 inches; for 4 feet, 6·212 inches; for 3 feet, 6·492 inches; for 2 feet, 7·135 inches; for 1 foot, 10·154 inches; for 11 inches, 11 inches; for 10 inches, 12·222 inches; for 9 inches, 14·141 inches.

Thus in order to catch any part of the real image of the landscape on the screen, we must place the screen in an appropriate position. Since we must put the screen in a different position with respect to the lens for each outward distance of objects in the landscape, we may comprehend that the **real image** of the whole landscape itself forms a **curiously distorted model** of the landscape, invisible and suspended in space **behind the lens**. In the instance just given, objects less than $5\frac{1}{2}$ inches from the lens do not form a part of the real image at all, but form a virtual image extending to infinity in front of the lens; objects from $5\frac{1}{2}$ to 11 inches in front of the lens are represented by the real image extending from an infinite distance behind the lens to 11 inches behind it; objects from 11 inches to 10 feet in front of the lens form a real image from 11 inches to 5·673 inches behind it; objects from 10 feet to 20 feet, from 5·673 to 5·629 inches; objects from 20 feet to 100 yards, from 5·629 to 5·508 inches; and all objects from 100 yards to an infinite distance have their real image compressed within a space from 5·508 to 5·500 inches behind the centre of the lens. The difference between the focal distance for an object at a distance of 20 feet and that for one at an infinite distance is thus small, being with a $5\frac{1}{2}$ inch lens 0·129 inch, and with a $3\frac{1}{2}$ inch lens only 0·052 inch. Hence instrument-makers construct small "fixed-focus" cameras, in which it is assumed that all objects more than 20 feet distant may be fairly in focus on the screen at one time; and ophthalmologists assume in practice that an object at a distance of 20 feet, or 6 metres, may be considered equivalent to one at an infinite distance.

When we put a screen in such a position S, Fig. 194, as to display the real image of any particular object, say one at 100 feet distance, sharply defined, the rays from more remote objects have already passed through their respective foci and come to diverge, while those from nearer objects have not yet reached their focus. The result is that each point of a nearer or more remote object forms, instead of a point on the screen, a "circle of diffusion," and the whole image of such objects is blurred and appears out of focus. The screen is too far forward for the nearer objects, and too far back for the farther ones. This result is explained by Fig. 194. Hence only one transversely-cut slice or section, or one plane of the landscape or object can be truly in focus at any one time: but if the circle of diffusion which represents each object-point be not too wide, say not more than $\frac{1}{100}$ inch in diameter, the result may be sufficiently satisfactory, and the lens is then said to have a certain "depth of focus," whereby it can form a satisfactory image of objects not situated exactly at the distance which gives the best definition on the screen.

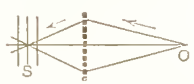

Fig. 194.

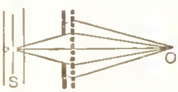

Fig. 195.

Let us use, close in front of the lens, in order to limit its breadth, an opaque disc with a central aperture in it; such a disc is called a stop: then as is shown in Fig. 195, the circles of diffusion are smaller, and therefore the definition of variously-distant objects on the screen is more nearly the same than it is in Fig. 194. Hence the definition of a landscape by a lens with a stop in front of it is sharper for all distances beyond and within the best-definition distance than it is when the lens is allowed a wide aperture; a lens when so stopped down therefore has its Depth of Focus increased; and this apart from all questions as to Spherical Aberration, of which later. Which gives the most artistic result—sharp diagrammatic definition all over the landscape, or the sharp definition of one object while the rest of the landscape is blurred, or an intermediate result obtained by a medium-sized stop—is a question of æsthetics into which we need not enter.

When therefore we use a **small stop**, the **angle** under which the rays reach the focus or screen is diminished; and the same result follows if we use a **long-focus lens**. Hence a long-focus lens is said to have greater Depth of Focus than a short-focus one of the same diameter; and generally, where an image real or virtual is formed by rays under **a small angle** of incidence, the lens or combination of lenses which form that image has **great depth of focus**.

The assumption of Fig. 193, that images of ex-axial points are in the same plane as images of axial points, is not true when the objects are of appreciable angular breadth, as viewed from the lens. The **image** of a **plane object**, produced by a single lens, whether that image be real or virtual, is not plane, but is **bowl-shaped.**

For example, in the convergent lens of Fig. 196, the object O is plane but the image is bowl-shaped. If therefore we try to receive this image on a screen, we find that if we put the screen at *a*, the peripherical parts of the picture are "**in focus**" while the central are not; and that if we put the screen at *b*, then, though the central part of the picture is distinct, the marginal part is blurred and "**out of focus.**" The reason of this is that the central part of the object is nearer to the refracting surfaces of the lens than the ends of it are, and consequently the image of the central part is farther away than the image of the extreme portions. Similarly if the lens be a converging one, but the object lie within the focus, the virtual image

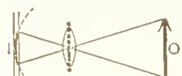

Fig. 196.

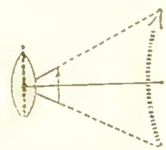
Fig. 197.

formed is again bowl-shaped, but with its convexity this time towards the lens, Fig. 197. Again, if the lens be a diverging one, the virtual image is bowl-shaped with its convexity towards the lens. Accordingly the virtual image in a **microscope** is bowl-shaped with its convexity towards the eye.

It is possible to a great extent to **moderate the curvature** of the image by using a lens more convergent than is necessary, and putting in front of it a plano-concave flint lens which tends to produce an opposite curvature; and by this means a fairly **flat field** may be produced. This lengthens the focus of the convergent lens and produces a larger and flatter image, farther off; and a lens so used is called an "**amplifier.**" An amplifier may even be used in conjunction with a microscopical objective for the **projection** of large pictures on a screen. The **eye-piece** of a microscope may be used for the same purpose, that of producing a large real image. The virtual image with which it deals must lie outside its focus; and this may be effected by raising the eye-piece, within limits; or by depressing the image formed by the object-lens, as by separating the object-lens and the object. The real image then produced on a screen is, for photomicrographical purposes, better than that which would be produced by the objective alone, in the absence of the eye-piece.

Thick Lenses.—In what precedes we have treated the lens as if it had no thickness, and had been reduced to a thin film of no appreciable thickness; and the Focal Distances and the respective Distances of the Object and of the Image have been treated as if they were distances from this ideal film. The next question is, **Where** is this **ideal film** supposed to be placed in relation to the Lens? As might be expected, this will depend on the form of the lens: and it might be said that the film is placed across the axis at a particular point of the axis called the **Optical Centre** of the lens. This leads to the inquiry, what is that Optical Centre?—but no better answer can be given than that it is the axial point of the ideal lens-film. This looks like arguing in a circle: but the student will see that if the ideal lens-film be itself an ideal merely, the optical centre must be equally **imaginary**: and he will not be surprised to learn that there is **not** in fact **any such point** in any single lens. On the other hand it is convenient, by way of simplification, to assume that there is a point on the axis which may be treated as the **centre** of the lens. If there were such a point, all rays **travelling towards it** before reaching the lens would appear to be travelling **from it** after traversing the lens: and the result would be as shown in Fig. 198. The non-axial object point O′ and its image I′ would be connected by a straight line passing through the Optical Centre C: and the line O′I′, from a non-axial object point O′ to the corresponding image-point I′, through the optical centre, would be a **secondary axis.**

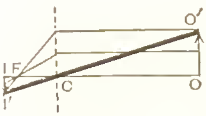

Fig. 198.

If however we take a real lens, say a biconvex one, and trace the rays, we find that the rays from O′ are **not in the same straight line** with those passing towards I′. More than that, the cases are very limited in which they can possibly even be parallel. There is, indeed only **one ray** from any given point O′ which can **emerge parallel** to its former course: this is a ray O′R, which meets the surface of the lens at such an angle that it is refracted along a course RR′, which takes it to a point R′ where the surface of the lens is parallel to the surface at R; so that the ray R′I′ is parallel to O′R. There is only one such ray from any given object-point O′; but in its course RR′ this ray, in the case of a **symmetrical biconvex** lens, crosses the axis at the very **midpoint** of the lens. All such rays as RR′, formed under similar conditions, come through the same point; and this point is then called the Optical Centre of such a lens. But it will be noticed that the **axes of pencils** of rays, before and after transmission respectively, **do not pass through** this point: the diagram shows that these honours are divided between two other points, which are called **nodal points** or **principal points,** N and N′:

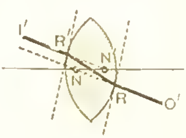

Fig. 199.

rays making for N **before** refraction appear **after** refraction as if they had come from N′, and the "**distances**" of image and object respectively are properly their respective distances not from the Optical Centre but from these **nodal points** N′ and N.

It is true that in a biconvex lens, both N and N′ are inside the lens, and are not very far from one another: and further, the thinner the lens the smaller will be their mutual distance, until when the lens is extremely thin we may neglect their mutual distance, and then assume both N and N′ to coincide with the midpoint of the lens. If we assume this, we may deal with the midpoint of the lens as if it were a true Optical Centre, the midpoint of the ideal refracting film of no appreciable thickness. But where we have an appreciably thick lens to deal with, or a lens of unsymmetrical form, or a combination of lenses, we see that a considerable inaccuracy is introduced by imagining that there is any one point which combines the attributes of both N and N′.

Let us, for example, take a **plano-convex** lens. The ray O′R is refracted into the course R′I′; and it emerges as if it had crossed the axis at N′. The point N is represented by the point R itself, the apex of the convexity of the lens; and as the lens becomes thinner, N′ approaches N or R until it ultimately coincides with it: so that it is said that R is the Optical Centre of such a lens, and distances are commonly measured from it; whereas the distance of the image ought to be measured from N′. Similarly, in a **plano-concave** lens the so-called Optical Centre is at the midpoint of the curved surface. If we take a **convexo-concave** lens (thin-edged) we find, as Fig. 201 shows us, that of the rays crossing the axis at N, that one which emerges parallel to its original course will appear to come from N′; but the so-called Optical Centre (defined as the point where a line joining the extremities of two parallel radii crosses the axis) is at C, farther away from the lens even than N. Observe that in this case the ideal refracting film is outside the lens, at a

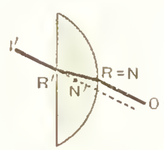

Fig. 200.

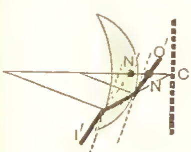

Fig. 201.

considerable distance from it. All this points to the fact that the results of our hypothesis that the lens is of a merely negligible thickness are approximate merely: but so long as we deal with single lenses the approximation thus obtained may be sufficient, though it is less close than is usually supposed. For example, let us suppose a convexo-concave thin-edged lens, with radii of curvature 12 and 9 cm. and an axial thickness of 0·8 cm., while the glass has an index of refraction of 1·5; then parallel rays, parallel to the primary axis and striking the concave face, come to a focus at a distance 67·59 cm. beyond the convex face; if they strike the convex face they come to a focus at a point 64·16 cm. from the midpoint of the concave face; and N and N′ are respectively at distances 1·47 and 1·16 cm. outside the vertex of the concave face: whereas the ordinary formulæ, which neglect the thickness of the lens, would represent this lens as a convergent lens of 72 cm. focal length. (See Fig. 203.)

We must therefore conclude that the so-called "optical centre" of a lens does not really correspond to any actually existing point, and is a mere convention, enabling us to make approximate statements and calculations. If we want to understand the action of any lens or system of lenses fully, we must trace out the position of the **nodal or principal points** N and N′; and in addition to these we must find the position of the two **focal points**, or points to which the lens or system of lenses makes parallel axially directed rays converge, according as these rays come from one side or the other.

As will be seen from the numerical example last given, these focal points are not necessarily equidistant from the lens itself; and they can only be equidistant from it when the lens itself is quite symmetrical in form.

We need not concern ourselves here with the circumstance that when the medium on both sides of the lens is not the same, there is a distinction to be drawn between the two principal points and the two nodal points. Principal points and nodal points are not the same unless the medium on both sides of the lens be the same, as it is with an ordinary lens in air.

Special Forms of Lenses.—There is a form of lenses which is sometimes required by the ophthalmologist, called **plano-cylindric** lenses. Suppose that a patient has the front of his eye "out of shape" so that it is like the side instead of the end of an egg. In such a case the eye is said to be **astigmatic.**

In one meridian the eye will be too sharply or too little curved: in a meridian at right angles to this the error may be less or may be opposed, or there may be no error at all. Suppose that the eye is too sharply curved in its vertical meridian while its horizontal curvature is normal: then the image of a point will be correctly focussed in a horizontal direction but will be blurred vertically, for the eye is practically short-sighted in that direction. The patient will in that case see points as short vertical lines, so that for example he can see nothing distinctly with a microscope. Let us suppose that this **vertical myopism** corresponds to an error of 2 D; if now we use a divergent lens of 2 D, we may correct the vertical myopia, but we at the same time gratuitously introduce a horizontal hypermetropia, with the consequence that the patient now sees points as short horizontal lines. What has to be done, then, is to grind a lens which shall have a power of 2 D in the vertical direction but none at all in the horizontal. This is accomplished by cutting a lens out of a cylinder of glass, by a section parallel to the axis. Such a lens looked at in one direction would have a cross-section like that of a plano-convex lens; and at right angles to this it would present parallel lines. Such a lens would not affect the horizontal focussing by the eye, while it would correct the vertical.

In regard to all spectacle-lenses, however, there is a considerable body of opinion that it is not well to have a convex or plane surface next the eye; for the distortion of objects a little to one side is too great. Hence "**periscopic**" lenses are a good deal used, in which the outer convexity is greater but in which the back of the lens is concave. As we shall see immediately, the three lenses shown in Fig. 202 might have the same focal length and correcting power, the factor $(1/r - 1/r')$ being the same in all; hence for axial rays they would serve much the same purpose, though the last causes the greatest amount of deviation of axial rays striking the outer part of the lens and consequently the least distinct vision axially; but the eye can be turned more comfortably into different directions when the third or periscopic lens is used. The axis of the eye is then, in all directions, more nearly at right angles to the general surface of the lens, and there is not, for this reason, so much difference between the appearance of objects straight ahead and objects above or below or to one side or the other, when the eye is turned so as to look directly at these.

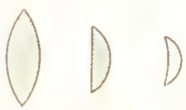

Fig. 202.

The same **periscopic** principle is applied in **cylindrical** lenses. Instead of say a plano-cylindrical lens whose curved surface has a radius of curvature of 30 cm., a plano-cylindrical lens would be taken whose radius of curvature was say 10 cm., and in the back of this a groove would be ground which had a radius of curvature of 15 cm. The concavo-cylindric lens thus produced would have a cross-section like that of a convexo-concave lens, Fig. 203: and its focal length would be the same as that of the 30 cm.-radius plano-cylindric lens; for $\frac{1}{10} - \frac{1}{15} = \frac{1}{30}$.

Focal Length of a Lens.—The **formula** usually given in order to find the focal length of a simple lens (neglecting the thickness) is $1/f = (\beta - 1)(1/r - 1/r')$, where β is the refractive index of the glass of the lens when the refractive index of air is taken as unity; r is the radius of curvature of the right-hand surface; r' is the radius of curvature of the left-hand surface; f is the focal length.

In Fig. 203 (a), let $r=12$ cm., positive, to the right; $r'=9$, also positive, to the right; $\beta=1{\cdot}5$; whence $f=-72$; and the focal length is 72 cm. to the left, or the lens is a convergent one of 72 cm. focus. If rays come from the left, we may turn the whole diagram upside down, and thus restore our working convention that rays always come from the right. The result is shown in Fig. 203 (b). The value of r is now -9, because the centre of curvature is to the left; that of r' is -12; the equation now gives us the same value for f, namely -72 cm.; or 72 cm. to the left. Hence, so far as this formula can show us, we might

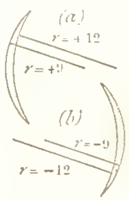

Fig. 203.

reverse a lens in its setting without affecting the focussing. But this is not so. If the lens be 0·8 cm. in thickness, the focal point will, in the case of Fig. 203(a), be not 72 cm. beyond the lens, but 67·59 cm. beyond it; while in the case of Fig. 203(b) it will be 64·16 cm. beyond it: and the Lens will only be **reversible** on condition that we make its **nodal points exchange places.** Then each Focal Point is situated at a distance of 66·12 cm. from the corresponding nodal point; and the two Nodal Points are at a distance 0·31 cm. from one another, both outside the convex face of this lens. If we wish, for any reason, to swivel the lens round, so as to reverse it, we must rotate it round a point midway between N and N′, so as to make these points exchange places: and it is only in a perfectly symmetrical lens that this point, which we may perhaps call the **swivelling centre,** coincides with the so-called Optical Centre of the lens. In the example given, this swivelling centre would be at a distance along the axis equal to 1·315 cm. in front of the vertex of the convex face of the lens.

The approximate **lens-formula** above given is applicable to **all forms** of Lenses, if we take care of our positive and negative signs. But it is far more accurate to make an actual **measurement** of the Focal Distance of a lens than it is to calculate out the focal length by means of a formula such as this, which neglects the thickness of the lens.

The distinction between the **Focal Distance** and the **Focal Length** of a lens is, though the two terms are often used synonymously, that the Focal Length is the true distance between the nodal point and the principal focus, while the Focal Distance is the distance between the actual lens and the principal focus.

The phrase Focal Distance is also used to mean the distance between the object and the lens in the everyday use of the lens. The student must therefore be on his guard, and must ascertain what is meant by the expressions focal length or focal distance, where these occur.

It is easy to find the **focal distance** of a convergent lens. Taking the rays of the **sun** as representing parallel rays of light, we may use our convergent lens after the fashion of a **burning glass** to make a sharply defined **image** of the sun on a **screen**: and we then measure the **distance** between the lens and the screen. If we do this with our lens of Fig. 203, we find a focal distance of 67·59 cm. on one side and of 64·16 cm. on the other side of the lens. Again, we may focus a **telescope** upon the moon or stars or upon a very distant object, so as to put it in focus for parallel rays: and then we may put the lens we are examining in front of the telescope, and in front of the lens some delicate object, whose position in front of the lens we adjust until we find that we can see it distinctly through the telescope. Rays **divergent** from the object are then transmitted by the lens to the telescope in a **parallel** condition; and the **object** is at a distance **from the lens** corresponding to the **focal distance** of the lens. The results obtained by this method are the same as those obtained by the last. Or again, we may take advantage of the proposition that when the **object** is at a distance equal to twice the Focal Length, the image is also at an equal distance on the other side of the lens: the image is therefore of the same size as the object. Accordingly we adjust the relative positions of an object (say a measuring scale), the lens, and a screen, until we find that the image on the screen is of precisely the same size as the object; then the distance between the object and the screen is equal to four times the focal length (*plus* the small distance between the nodal points, which we neglect). In the instance of Fig. 203, this method would give as its result a focal length of 66·20 cm. The True Focal Length, the distance between either nodal point and the corresponding focal point, is in this case 66·12 cm.; so that method (3) gives the closer approximation to the true focal length.

For symmetrical convergent lenses, in which the focal distance is the same on both sides of the lens, Bessel's method is very ingenious. Fit up a bright object O and a screen I at a known distance OI apart; move the lens gradually from O towards I until a sharp magnified image of O is formed on I; then note the position of the lens, say at A. Next move the lens still nearer to I, until a point B is reached at which a sharp diminished image is formed on the screen; note the length of the line AB. Then the focal length is $(OI^2 - AB^2) \div 4OI$; and the quantities in this expression are easily measurable.

The focal length of a divergent lens is not so easy to ascertain. Practically it is found by ascertaining to what extent it will weaken a stronger convergent lens. A convergent lens of known focal length f is taken: the lens to be tested is brought into contact with it; the combination must still retain some convergent power, or if it does not, a stronger convergent lens must be used; the focal length F of the combination, considered as a single convergent lens, is found as above: it is then assumed that both lenses are mere films and are coincident in position; and this assumption enables us to apply the formula $1/f + 1/f' = 1/F$, in which we know f and F and can accordingly readily calculate out the value of f', the focal length of the divergent lens. The value so obtained is generally only a very rough approximation to the true Focal Length f': but it has a value of its own; being an experimental result it enables us to state the effective weakening power, $1/f'$, of the lens when used in combination with a convergent lens, and in contact with it. On the other hand, it does not enable us to use the figure so obtained as a datum of the value of f' in problems involving the use of lenses not in contact with one another: and in order to work out calculations of this order we must ascertain the curvatures of the divergent lens, its axial thickness, and the refractive index of the glass of which it is composed, so that we may learn its Nodal Points and its true Focal Length by means of the more complicated formulæ already alluded to, which take account of the thickness of the lens.

Angle of a Lens.—There is a short-hand way of noting the course of rays in a lens which it may be useful to explain, and which we have already used at Figs. 196 and 197. Suppose we have a lens of known focal length, and an object at a known distance *d*: then, neglecting the thickness of the lens, the diagram of the course of the rays would be, if the lens be a convergent one, as in Fig. 204 (*a*). But for many diagrammatic purposes it is quite unnecessary to put in all these lines: and it is often quite enough, for such purposes, provided that we do know the respective distances *d* and *d′* of object and image, to represent the action of the lens as in Fig. 204 (*b*), where the distances are simply drawn to scale.

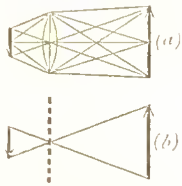

Fig. 204.

This shows that the picture on a photographic plate has been taken under a certain **angle**: and if we look at a photograph with one eye under this same angle, putting the **eye** where the **camera-lens** had originally stood, we view the photograph as the camera-lens had viewed the landscape, and we then see it in **perspective relief**, though with one eye only.

When we take into account that we have to do not with a true optical centre, but with Nodal Points N and N′, the diagrams become as in Fig. 205, where (*a*) shows the effect of a convergent lens producing a real image, (*b*) that of a convergent lens producing a virtual image, and (*c*) that of a divergent lens producing a virtual image.

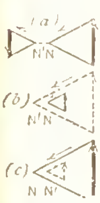

Fig. 205.

Magnification by a Lens.—The term **Magnification**, or **Magnifying Power** of a Lens, seems somewhat ambiguous. Let us say that a given convergent lens has a magnifying power of 5 diameters. Then the Virtual Image is formed at a distance of say 10 inches when the Object looked at through the lens is at a particular distance from the eye: and this distance will, in this case, be 2 inches. An object at 2 inches from the eye is too near to be seen: and the lens enables it to be seen distinctly as if it were a larger object situated at the Least Distance of Distinct Vision. Fig. 206 shows that the near object O is simply rendered visible as if at I, subtending (if we neglect the thickness of the lens) the original angle at the optical centre of the lens, without change; and the image is larger than the object in the ratio 10 : 2, or 5 : 1.

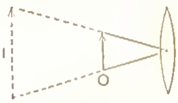

Fig. 206.

Generally, if d and d' be the respective distances of the object and the image from the optical centre (or more accurately, from the corresponding nodal points), the Magnification $m = d'/d$. If the image be nearer than the object, d' is smaller than d, and the magnification is a fraction; that is, there is a "diminishing" effect.

The case shown in Fig. 206 is not easy to realise, since the combination of a lens *plus* the seeing eye is not the same in its action as a simple lens alone: but if the eye look partly through and partly over the edge of a thin-edged lens held as close as possible to the eye, so that both the object and its image are viewed at the same time, it is easy to show that both the **object** and the **image** tend very nearly to **cover the same field of view**, and to differ only in distinctness, not in size. They therefore subtend the **same angle** at the Eye.

Where, however, the eye is not laid so close to the lens as this, the state of matters is different. In that case the **object** stands at a certain distance from the Eye, and subtends a certain **angle at the eye**: the **image** also stands or seems to stand at a certain distance from the eye, and subtends or seems to subtend a certain **angle at the eye**: the two Angles subtended are in most cases **not the same**, and hence there is a difference in the **apparent size** of the image and that of the object, as seen from the Eye. Fig. 207 shows how the result of

Fig. 206 is modified when the eye retreats to a distance from the lens. The object and the image subtend equal angles at the lens, but not at the eye: and the image appears larger than the object in the ratio of AB to EF. This ratio of AB to EF will **vary** with every position of the eye and with every adjustment of distance between the object and the lens.

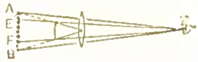

Fig. 207.

To take an extreme case, fit up a lens so as to form an image of a distant window on a page of printed matter: make that lens move towards the paper through a very short distance; then go backwards towards the window, still looking through the lens; the printed matter will appear extremely distant and huge in size in comparison with the printed characters themselves, for the virtual image of these is large and remote.

Hence we have two things to distinguish; Magnification as a measure of **enlargement** of the **image** formed at a **standard distance** (10 inches) from the eye; and Magnification or Amplification as a measure of the **greater visual angle** under which the **image is seen** through the lens (or system of lenses) employed. The former is of importance in the **microscope**; the latter in the **telescope** and **opera-glass**.

In the former sense, the Magnification produced by a convergent lens of 4 inches focus is $3\frac{1}{2}$ times; for $m = d'/d$: and when $d' = 10$ inches, $d = 2\frac{6}{7}$ in.; so that $d'/d = 3\frac{1}{2}$. But in the latter sense, the Apparent Magnification depends on the relative positions of the object, the lens, and the eye: for example, if the object be at 3·9 inches from the lens, and the eye 32 inches on the other side, the image seems 13 feet away, while the apparent diameter of the image is 29·7 times that of the object.

The apparent Amplification is equal to the **ratio** between the **tangent** of **half the angle** subtended at the Eye by the **image**, and that of **half** the **angle** subtended at the eye by the **object**. When the Eye practically coincides with the Lens, the amplification in this sense is **unity** only, for both angles are the same; but in that position the **angle** which the image subtends at the Eye is the **greatest possible**. There certainly is a contrary impression produced on the mind—an erroneous one, however—that the image is more highly magnified, in the sense of subtending a greater visual angle, when the object—say a book—and the lens—say a reading glass—are used at arm's length. The angle subtended by the virtual image is in that case really smaller than when the lens is used at close quarters; and so is the image on the retina; but there is in the first place an obviously greater **angular amplification**, as may be at once seen on comparing the printed page with its virtual image, and in the next place there is a greater amount of **comfort** in using a lens under such conditions, since the Accommodation of the eye is not strained as it is when we look at an image at the least possible distance of distinct vision. On the contrary the image is then **thrown back** and is very **large**, so that the effort which the Eye has to make is much the same as that which it would have to put forth in reading a **poster on a wall**.

Combinations of Lenses.—When we have to deal with a combination of lenses instead of with a single lens, there is one **guiding principle** which helps us through our calculations. This is, that we may consider **each lens separately** and dispose of its action before going on to the next. If we have an Object in front of the **first lens** of a combination, that lens must necessarily form or tend to form an **image somewhere**; and this image may, according to circumstances, be **real or virtual.** But the rays, now diverging from a real image or converging with the view of forming one, or diverging as if from a virtual image, are acted upon by the second lens, and this **second lens** makes or tends to make a **second image** of the original object. So on; the last lens of the combination is bound to make a Real or a Virtual Image somewhere along the line of light.

Take an opera-glass, closed or very slightly lengthened at haphazard. We can see nothing when we look through it: this is because we cannot see the image; but the **image exists**, or tends to exist, either as a Real Image somewhere in space between the eye-piece and an infinite distance behind the eye, or else, if the tube be somewhat lengthened, as a Virtual Image inside the tube of the instrument, but too near the eye for the eye to be able to see it distinctly. As the tube is further lengthened, the image, virtual within the tube, **shifts forward**, away from the eye, until at length it reaches a position where the **eye** can conveniently **inspect** it without strain.

What is called **focussing** of such a combination as an opera-glass, a microscope, or a telescope, implies **shifting** the Image, which is always really or virtually formed somewhere, into a position where the **eye** can comfortably inspect it; and the **focussing** of the image on a **screen**, say in photographing a microscopical preparation, implies shifting the real image backwards or forwards until it comes to **coincide** with the screen, or else shifting the screen until it comes to coincide with the image.

It is sometimes necessary to produce an image of a **determinate size** on a screen. Suppose we want a **larger** image than we actually get sharply defined: we must move the **screen** to a **greater distance**, and then make the lens and the object approach one another so as to throw the **image farther off**, and make its position coincide with that of the screen. Conversely, if we want a smaller image, we must separate the lens from the object. When a **microscope** is used for **photographing**, the larger the picture required the more closely must the front lens and the object approach one another; or in some cases, as in **Abbé's projection oculars**, the more closely must the uppermost lens and the last real image within the microscope tube approach one another, for a real image always acts as if it were a real object. When a lens of **short focus** is used in a **photographic camera** in order to make a picture of a given object and of a **given size**, it must come **nearer** the object than when a lens of longer focus is used. The tendency to form larger images of nearer and smaller images of more remote portions of the object is thus exaggerated. In the photography of **surgical cases**, where it is of importance that the photograph should represent the true form, the **longest focus** lens which is convenient should be used, the object being then placed at a correspondingly **great distance** from the camera.

Equivalent Lens.—**Parallel** rays, entering a combination of lenses, mostly emerge in a state of Convergence or of Divergence, according to the nature and arrangement of the lenses in the combination. They have therefore been, on the whole, **deviated** to a certain extent; and the **simple lens** which would produce the **same deviation** is called the **Equivalent Lens**. Any combination of lenses is, so far as regards the Deviation produced by it, equivalent to such an equivalent single lens; but it has its **nodal points** in most instances much **farther apart** than they could possibly be in a single lens.

The **nodal points** have thus an importance in a **combination of lenses** far exceeding that which they can possess in a single lens: but the properties of the nodal points in a lens-combination in no way differ from those of the nodal points of a single lens.

In Fig. 208 let the nodal points of a **convergent** lens or combination of lenses be N and N′, and the principal foci be F and F′; and let O be an **object point**. Join ON: the ray ON emerges from the lens parallel to ON, but directed as if from N′; therefore draw N′I, parallel to ON. Again, draw a ray from O parallel to the axis, as far as the point M, in the plane cutting N′: this ray goes to the principal focal point F: therefore join MF and produce it until it cuts N′I in I; I is the **real image** of the object-point O. The student may exercise himself in showing, on the same lines, how a **virtual image** is produced if O lie between N and F′. The rays N′I and FI do not, in that case, converge and meet in I, but they diverge as if from a point behind (to the right of) N′.

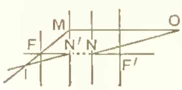

Fig. 208.

Again, with a **divergent** lens or combination, the corresponding diagram is as in Fig. 209. Join ON; continue the ray, but as if from N′. Again draw OM as before: the emergent ray seems to come from F, along FM. FM and the ray through N′ travel *as if* they had intersected at I; I is the **virtual image** of the object-point O.

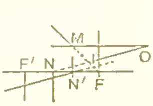

Fig. 209.

The distinction between the fictitious Optical Centre of a lens and the two Nodal Points of a lens disappears when the light does not emerge at the back of the lens. There is then only **one refracting surface.** Let the glass lens (Fig. 210) have a front surface F of spherical form, of which the centre is C; and let the back B be also spherical, with the same centre. Let the object O be spherically bowl-shaped, also with the same centre C. Then if the glass be sufficiently refractive, or the lens FB be long enough, the

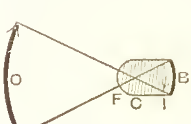

Fig. 210.

image I will be formed within the lens: and it will be spherically bowl-shaped, with the same centre C. This centre C is a **true optical centre**; and it is also said that in such a case there is only **one nodal point**, which is also the point C. If the lens FB be of the right length, I will coincide with B, and the image of the object O will be formed on the back B, which may be blackened.

In works on Physiology, the student will find that the **Eye** is for simplicity's sake reduced to an **ideal eye** of this kind, which is formed of **water** standing **in air**, and whose curvatures are not the same as those of the actual eye: and then the true optical centre or single nodal point of such an ideal eye is called the "Nodal Point" of the actual eye. But the **actual eye**, as a combination of lenses, has **two nodal points**, near one another **within the crystalline lens**; and the single so-called Nodal Point of the ideal eye lies **between these**. The use of this device enables diagrams to be simplified without too much inaccuracy.

In **myopic** eyes this point is, relatively to the bulb, too far forward; it is therefore farther from the retina or back of the eye; and **images** formed on the retina are therefore **larger** than they are in the case of normal-sighted persons.

Centring.—In all combinations of lenses it is of importance that the component lenses should be well **centred**; that is, that their axes should all lie in one and the same straight line. If this be not attended to, the resultant image is thrown off to one side, so that it **rotates** when the lenses which are in fault are rotated; and it lies at **an angle** to the general axis of the apparatus, so that only **one strip** of it can be brought to **focus** at any one time.

This consideration is of great importance in the adjustment of **spectacles**: for if the optic axes of the lenses do not coincide with the optic axes of the eyes, there is great strain put upon the eyes, which suffer. Again in the use of **binocular** telescopes, opera-glasses, microscopes, and the like, the distance between the two oculars should always be **adjustable**, so that it may be made to agree with the distance between the centres of the pupils of the two eyes. The different parts of the **eye** seem to be never thoroughly well centred on the optic axis.

Spherical Aberration is a fault inherent in lenses and combinations of lenses ground in the usual way with spherical surfaces. Its nature is illustrated by Fig. 211. The rays striking the axial part of the lens come to a focus at F; the desideratum would be that those striking the peripheral part of the lens should come to a focus at the same point F. This would imply that the peripheral parts of the lens should present a suitable slope for this purpose; but no such slope is obtainable with spherical surfaces. The result is that the rays striking the peripheral part are always, in a biconvex lens, refracted too much, and come to a focus at F′. Hence if we cover up the peripheral part of the lens, the focus is at F, whereas if we cover up the central part of the lens, it is at F′. The distance FF′ is called the longitudinal spherical aberration. If the screen be brought up to the position F in which the axial rays are in focus, the peripheral rays, having already met, are already divergent, and the result is that the image of a point is spread out into a disc, whose diameter is GH. The diameter GH is called the lateral spherical aberration.

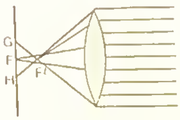

Fig. 211.

The most obvious means of checking Spherical Aberration would be to limit the diameter of the lens by means of a stop; but this would have the effect of diminishing the amount of light available.

The theoretical way to get rid of Spherical Aberration, in a lens of the required aperture, would be to employ not spherical but ellipsoidal or hyperboloidal surfaces; but this remedy cannot be employed in practice. An ellipsoidal or hyperboloidal surface may refract light coming from a point at a definite distance in one medium so as to bring the rays to a point-focus within the second medium; and this correction is present in the human Eye. A lens gradually increasing in refractive index from its surface to its interior might avoid this fault: such a lens we actually find in the crystalline lens of the human Eye. What is done in the practice of lens-makers is to use spherical surfaces and then to correct these. In exceptional cases the surfaces themselves are altered slightly by careful polishing, so as to vary the form of their curvature, this being done by a systematic process of trial and error. In ordinary apparatus, however, the use of properly placed **diaphragms** is of advantage. Such Diaphragms allow central rays to traverse the lens centrally: but the only rays which can reach the margin of the lens are rays from marginal parts of the object; such rays, falling (Fig. 212) at a greater angle of incidence upon the peripheral parts of the lens, have their focus thrown well forward; and thus the whole of the rays which can traverse the lens all come to focus in the neighbourhood of F, the focus for axial or central rays. The **iris** acts as an **adjustable diaphragm** in the human eye, and not only regulates the amount of light which is admitted, but also tends to subdue spherical aberration. Again, the form of lenses may be so devised, even with spherical surfaces, as partially to obviate or avoid this fault. If we have an object at a distance d, the best form of the lens to be employed in order to make a clear image of that object will depend upon that distance d. The limits of this are, for example, that when the lens is of refractive index $1\frac{1}{2}$ (crown-glass) and the object is at infinity, the radii of the biconvex lens, nearer and farther from the object respectively, must be as 1 : 6. As the distance diminishes the ratio changes, until when the object is at the principal focus the ratio of the radii should be 6 : 1. Such lenses are called **Crossed Lenses**.

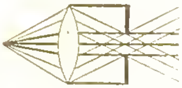
Fig. 212.

Again, in **combinations** of lenses called **Aplanatic** combinations another principle is utilised. In a thick-edged lens the spherical aberration is opposed to that of a thin-edged one; the point F lies behind F′. If we **combine** a thin-edged lens with a weaker thick-edged one, there is a tendency to **compensation** of the errors due to each lens singly; and by suitable choice of the refractive indices and curvatures of the two lenses, the **correction** may be made very nearly perfect. Lastly, it is found that there is less spherical aberration when we use instead of a single biconvex lens a **series** of **weaker** lenses: for in that case the marginal rays are gradually brought more nearly into line with the axial rays, and are on the whole more acted upon by central parts of the lenses; and thus the aggregate differences of slope between the refracting surfaces which deal with marginal and those which deal with axial rays are on the whole diminished.

Combinations of lenses in which the Spherical Aberration is **got rid of**, by adjusting the curvatures and refractive indices of the different lenses which make up the combination, are said to be **aplanatic.**

Combination in which the spherical aberration is **incompletely** got rid of are said to be **under-corrected.**

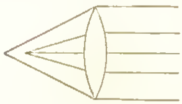
Fig. 213.

Combinations in which the correction for spherical abberration is too great, so that the peripheral rays come to a focus **beyond** the axial, as in Fig. 213, are said to be **over-corrected.**

It is not possible to make any combination of spherical-surfaced lenses which shall be perfectly aplanatic under all circumstances. If such a combination be aplanatic for parallel rays, and thus bring all parallel rays to the same focus, it will not be perfectly aplanatic for convergent or divergent rays. If it be aplanatic for rays coming from a point in or near the axis and a little beyond the focus, it will be somewhat spherically-aberrant for points beyond that: and again, as the object approaches the lens-combination, this acts first more and more decidedly as an "over-corrected" combination, then less and less so, then as an aplanatic, and lastly as an under-corrected combination. The two points, in reference to which the combination acts aplanatically, are called the "**aplanatic foci.**"

Both over-correction and under-correction act detrimentally on the performance of a lens. To begin with **under-correction**, or residual ordinary "**positive**" Spherical Aberration. The ideal to be sought after is, naturally, that all rays from a point in the object should come together at a single point in the real image, and diverge therefrom as from a single material bright point. But if there be Spherical Aberration (non-corrected or under-corrected), the result is that shown, in an exaggerated form, in Fig. 214.


Fig. 214.

The image is most distinctly seen at I, but is shrouded by a haze of light from the peripheral parts of the lens, which light has already come to a focus and diverged. At I′, farther from the lens, the image becomes more dim and foggy; and at I″ the point O produces, as its image, a disc. Towards I''' this disc enlarges. Hence if the lens and object be brought to the position in which the best definition occurs, at I, and if the screen or eye-piece be then brought slightly nearer to the lens, there will be less fog, but each bright point of the object will be represented by a disc of light.

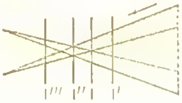

Fig. 215.

If the lens be, on the other hand, an over-corrected one (showing "negative" spherical aberration), the results are indicated in Fig. 215, which is exaggerated in the same way as Fig. 214.

Here the conditions are exactly reversed: when the screen or eye-piece is brought *nearer* the lens than I, the resultant image is more foggy.

When the lens and the object are separated, the effect is as if the screen were shifted towards the lens; and with an over-corrected lens the image becomes more foggy, with an under-corrected lens less foggy.

The hazes or fogs referred to may be readily observed by taking an ordinary single lens, with a candle flame at some feet distance: if we try to make an image of the candle flame on a screen, it will be observed that there is a lack of brightness in the image, and a halo round it. If a plano-convex lens be used, it will be observed that this effect is much more pronounced if the plane side of the lens be towards the distant candle than it is when the convex side is towards it. Conversely, if we want to produce a fairly uniform parallel beam of light by means of a candle near at hand and a plano-convex lens so placed that the candle is in its focus, it is much better to turn the convex side of the lens towards the candle, for the spherical aberration is in that position only one-fourth what it is when the other side of the lens is turned to the light.

It is important that a lens or a system of lenses should be aplanatic when it is intended to use it as a condenser. The problem here is—Given a parallel beam of light, how is that light to be brought to bear upon a point in a transparent object, so that that object may appear to shine by its own light? Necessarily the answer is that both the axial and the peripheral parts of the beam must come to the same focus, and the point of the object which it is desired so to illuminate must be put in that focus. But the axial and the peripheral parts of a parallel beam, or indeed of any beam, can only be so brought to a single point by an absolutely aplanatic lens-combination, which is at the same time well achromatised; and hence the value of the "**achromatic condenser**" in microscopy. By this appliance a parallel beam of light, obtained by means of other devices, is concentrated upon a point of the object, which point in its turn acts as a source of light-waves.

It is found that the best results are obtained when the **condenser** brings light to the object under the **same angle** as that under which the **objective** receives light from it, as in Fig. 216: for in that case the **Diffraction-Fringes** (p. 346), which tend to blur the resultant real image, are reduced to a minimum breadth, and the outline of the object is most clearly defined.

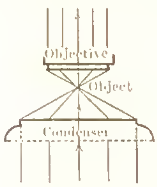

Fig. 216.

If by any means the Rays sent through a spherically-aberrant lens were **reversed**, their respective paths would be retraced; the lens would **correct the errors** and return the rays in a **parallel** or otherwise uniform beam. If, accordingly, the **rays received** by a spherically-aberrant lens happened, for any reason, to have courses **resembling**, in a **reversed direction**, those into which a parallel beam would be thrown by the Spherical Aberration of that lens itself, that lens would make them **parallel**.

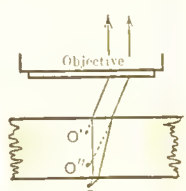

Fig. 217.

This is applied in the **correction-objective** of a **microscope**: by rotating the correction-collar of the objective, the lens-system is somewhat distorted, through approximating the lenses of the objective (generally by making the back-lens approach the front one); and the lens-system is thus rendered somewhat spherically-aberrant or "**under-corrected.**" The rays from the object O (Fig. 217), when they have traversed **the cover-glass**, do not reach the lens as if they had truly diverged from O, but as if they had come from a series of points ranging from O″ to O′. But if the objective be under-corrected, the distance O″ O′, in air, may precisely be the Longitudinal Spherical Aberration of that objective; and if that be so, the objective will collect the rays and transmit them uniformly. Hence by adjusting the amount of under-correction of the objective, the objective may be made so to refract the rays from O that these travel as if from a somewhat nearer point, with no intervening cover-glass: and the adjustable collar thus enables cover-glasses of any thickness to be used.

Distortion of Images.—The **farther** any given point of the **object** is from the **axis** of a **thin-edged** lens, the **less** is the **proportionate distance** of the corresponding part of the **image** from the axis: and conversely, in a thick-edged lens the greater is that proportionate distance. The result is that if we try to make an image of a square set of black lines ruled in squares, a biconvex lens distorts the image into a **barrel-shape**, its corners being squeezed in; and a biconcave lens distorts it into what is called an **hour-glass** shape, a square with its corners pulled out and its sides concave outwards. This defect, being a consequence of Spherical Aberration, is remedied by correcting that aberration.

When a photograph of a determinate size has to be made, say on a "quarter-plate" ($4\frac{1}{4} \times 3\frac{1}{4}$ inches), if we use a **short-focus lens** the plate subtends a **wider angle** than a plate of the **same size** would do in a more extended camera with a longer-focus lens. On a given plate, accordingly, a shorter-focus lens will operate under a wider angle, and the resultant picture will represent a **wider expanse**, than where we have a longer-focus lens used with the same plate; but this use of lenses under wide angles brings in, with simple lenses, a certain degree of **distortion** of the circumferential portions of the picture. This distortion is considerably less in the case of the long-focus lens, merely through the plate not being large enough to take in more than a limited central portion of that image which the lens has the potentiality of producing. Long-focus lenses would distort quite as much as short-focus lenses of the same form, if we used them under equal angles and with objects whose scale, linearly, was proportional to the linear dimensions of the lens; but for objects and images of a given size, the larger the lens, that is, the longer its focus, the less the proportionate distortion. In photographic lenses, therefore, the wider the angle the greater the tendency to distortion by a **single lens**: but modern lens-makers have expended great skill in shaping and adjusting **combinations** of lenses so as to get rid of this distortion as far as possible.

In respect of all lenses it is to be noted that lines which are **vertical** and **parallel** to one another in the **object** will not appear vertical and parallel to one another in the image received on the screen, unless the **screen** be also **vertical**.

Hence it is essential in the use of a Photographic Camera that the ground-glass **screen** should always be kept **vertical** by the use of the **Swing-back**. Then if the camera have to be pointed upwards, say towards a building, the screen must be sloped forward so as to remain vertical, and then the vertical lines of the building appear vertical in the resultant picture; whereas, if the ground glass be kept at right angles to the axis of the camera, the resultant picture will in that case represent buildings, etc. all sloping backwards and standing upon level ground.

Chromatic Aberration.—In simple **convergent** Lenses, the **more refrangible** violet and chemical rays either **converge** upon a **nearer** focus, or seem to diverge from a more remote point than the less refrangible yellow and red. In simple **divergent** lenses, the virtual focus for violet is **nearer** to the lens. The consequence is, for example, that the image of a very small bright **point**, formed by a convergent lens and thrown upon a screen or received in the eye, is surrounded either by a red or a blue **halo**. In the former case the red rays have not yet come to a focus: in the latter the blue and violet have already traversed their focus, and are already diverging.

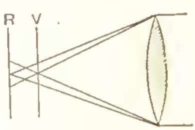

Fig. 218.

The distance RV between the focus for red and the focus for violet rays is called the **longitudinal chromatic aberration** of the Lens; the diameter of the halo, at any point between the focus for red and the focus for violet, is called the **lateral chromatic aberration** at that point.

If the object be an extended one, one of some breadth, the halos belonging to the different points of the object will overlap one another; but the edges of the object, or of differently illuminated portions thereof, will appear coloured.

In a simple convergent lens, say of crown-glass, Chromatic Aberration is got rid of and the lens **achromatised**, so that it gives images not coloured at the edges, by combining with it a weaker divergent lens of flint-glass.

The **combination** acts as a **weaker lens**; but if the curvatures and the refractive indices for the different colours be properly chosen, the **irrationality of dispersion** between flint-glass and crown-glass comes into play, and two selected colours, say blue and red, are brought to the same focus. For ordinary **microscopic objectives**, the colours so dealt with are usually extreme blue and yellowish-green. If three lenses be used, three colours may be brought to the same focus; and so on; but this more complicated achromatic correction has only been readily attainable since 1886, when the new varieties of Jena glass came into the market. In **photographic lenses**, the aim is to bring average actinic and average visible rays (or in some cases, merely blue and violet) as nearly as may be to the same focus; so that it is quite possible that a lens which is really a fine one from the photographic point of view may appear somewhat non-achromatic if used as the object-glass of a telescopic combination; and on the other hand there have been photographic lenses made, as for Rutherford's lunar photographic work, in which the aim has been to bring the actinic rays all to the same focus, and by means of which photographs of extraordinary clearness have been taken, while the definition of the visible image on the screen remains somewhat blurred.

If one of the lenses have a plane face while the other lens is symmetrical, as in Fig. 219, the difference of dispersive powers must be in F twice as great as in C; for the two curved surfaces of C are of the same form as the single refracting surface of F. In flint-glass the difference of dispersive powers is more than twice as great as in crown; so that the curvatures must be somewhat modified. Then when the curvatures have been settled for Chromatic Aberration, they may again have to be altered in order to deal with Spherical Aber-

Fig. 219.

ration; so that Fig. 219 may have to be altered into Fig. 220 in order to secure this end. This change need not affect the focal length or the chromatic-aberration correction: but it is always desirable to shape the crown-glass lens symmetrically, since this involves, on the whole, the least difficulty in grinding the lenses to the required curves.


Fig. 220.

Chromatic aberration may be remedied in a lantern condenser by adjusting the mutual distance of the two component lenses until the divergent spectrum-forming rays have so far separated that the violet rays fall upon a part of the second lens distinctly less refracting than the part upon which the red rays fall. By this means both rays may be made to emerge parallel. Conversely, parallel rays of white light are brought approximately to the same focus O.


Fig. 221.

If a lens or combination of lenses be corrected for Chromatic Aberration in respect of rays parallel to the axis, it may very well fail in this respect when the rays fall upon it obliquely; and in general there is always a certain amount of coloured fringe (the so-called "secondary spectrum") round the image of any bright object seen through a lens against a black background, or black object seen against a bright background, this fringe being due to the imperfect correction for colours other than the particular pair for which Achromatism has been attained.

It may always be ascertained whether a lens is achromatised, by covering half of its aperture with a slip of black paper: then, as an object, view through the lens a small hole in a black plate, held up against a bright light. If the lens be under-achromatised or not achromatised at all, there will be more refraction of the violet than of the red rays, so that the image of the bright hole in the black plate has a blue or violet border on the side corresponding to the black paper, and an orange or red border on the side corresponding to the free border of the lens. If on the other hand it be over-corrected, it will present precisely the reverse phenomena: and if it be accurately achromatised, there will be no such fringes. It is possible that different parts of the lens may differ in respect of the completeness with which achromatism has been secured.

This may be ascertained by putting the lens in the path of parallel rays of light and moving about, as an object looked at, a minute hole in a black plate with a bright background. It may be found that the hole appears colourless when opposite the centre of the plate but colour-margined when near its periphery. Chromatic Aberration may be observed in the **human eye** if a window, with window-bars, be looked at past the edge of a black card: the edges of the window-bars then appear fringed with colour. In that event only half the eye is in use: and when the whole eye is in use these colour-margins all overlap one another, and produce together a total effect of **fogging** the general picture by a haze of white light, an effect of which we are not generally conscious. If heat-rays and ultra-violet actinic rays had given rise to visual sensation, this haze would be so well marked as to blur our visual perception of external objects. As it is, equally-distant differently-coloured objects are not in focus at the same time; when we look at equally-distant red and blue objects we are quasi-short-sighted for the blue ones, which appear farther off.

Microscopic objectives which are achromatised for three colours and have their spherical aberration corrected for two colours are called **apochromatic** lenses.

Optical Instruments.—In the **Astronomical Telescope** we have first an **object-glass**, that is, a convergent lens (usually an achromatic doublet), which forms an inverted **real image** in the telescope tube: the other end of the instrument bears the **eye-piece**, a convergent lens (or achromatic combination of lenses) which is moved backwards or forwards until it comes to stand in a proper position in relation to this real image. In this proper position, that **real image** is used as an **object for the eye-piece**, at such a distance from it that a **virtual image** is formed at the Least Distance, from the eye, for Distinct Vision. In fact, the eye-piece acts as an ordinary magnifying glass wherewith the Real Image is examined, as if that real image were an ordinary object brought to a certain distance from the eye-piece. And as we have seen before, the real image of nearer objects will be farther from the object-glass than the image of farther objects; so that the **eye-piece** must be moved **away from the objective** in order to examine the image of **nearer** objects, and must be moved towards it in order to examine that of farther ones. This description applies properly to the astronomical refracting telescope, as also to certain "night-glasses," which give an inverted image. In Fig. 222 the real image within the telescope tube is at R, and the resultant virtual image at V; and the virtual image, though much smaller than the distant object, subtends a greater angle at the eye of the observer than the distant object could itself do. (Compare Fig. 207.) Hence if the object be looked at through the telescope with one eye, and be looked at in the ordinary way with the other eye, the telescopic image will appear considerably larger than the object itself does.

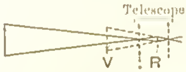

Fig. 222.

In the ordinary **Terrestrial Telescope**, the eye-piece is not left in the above simple form: some device has to be adopted in order to **reinvert** the image so as to make it **erect**, like the original object itself. This is effected by using a **second lens** (or usually a combination of lenses) which shall treat the first Real Image, produced by the object-glass, as its object, and shall produce a **second real image**, an inverted image of the first inverted real image, further up the instrument, that is, nearer the eye. This **second inversion** has, of course, the effect of making the second real image **erect**. Then the **eye-lens** examines this second Real Image, and makes a Virtual image of it. As might be expected, single lenses cannot be used in actual instruments, for each lens must be achromatic and aplanatic: and this can only be secured by transforming each single lens into an appropriate corrected combination.

The terrestrial telescope, with its erect image, has been modified for the examination of near objects in Ploessl's **dissecting microscopes.**

In the **Opera-glass** there is, in front, a **convergent** lens (the **object-glass**) and at the eye a **divergent** one (the **eye-piece**). The object-glass tends to make a Real Image behind the eye-piece: but the eye-piece is moved back until it gets into a position where, catching the converging rays, it makes them diverge as if they had come from an erect **virtual image**, about 10 inches in front of the eye or, generally, at the minimum distance for distinct vision. But this position is one in which the Accommodation of the eye is strained to the utmost; and it is better to withdraw the eye-piece still farther from the object-glass, and thereby to **throw** the **virtual image forward**, so that we may look at it more comfortably. This throwing forward of the virtual image reaches its **limit** when the Real Image tends to be formed by the object-glass at a point corresponding to a principal Focus of the eye-piece; then the rays emerge from the eye-piece as if from an object at an **infinite distance**.

In the Telescope and Opera-Glass, **light** falling on a comparatively large object-glass is **concentrated** so as to fall within the **pupil of the eye**: and thus objects which are too dim, for want of light, to be readily seen by the unassisted eye may be distinctly seen by their aid.

Opera-glasses are very useful in this respect, and may be used in a comparatively dim **twilight** or dusk. They are used in some college classes on the Continent in order to look at lantern-projections which are too dim on the screen to be seen in the ordinary way by the unaided eye. Mr. Francis Galton found them useful at night in South Africa. Where the difficulty of seeing objects arises from **want of light**, the larger the object-glass the better: for example, for seeing nebulæ by means of the astronomical telescope a **large aperture** is required. But for **resolution of detail**, where the light is sufficient, it is, in telescopes and opera-glasses, not width of aperture but **accuracy of correction** which is necessary: and a smaller telescope, if a fine one, may resolve detail which one of larger size may be unable to grasp.

In the **Microscope** there are two modifications. The easier one to understand is the microscope fitted with a Ramsden eye-piece, which is, however, not the usual form. In this case the **objective**, a lens-combination of **short focus**, with its **nodal points** very nearly coinciding with the terminal faces of its lenses, forms an **inverted real image** situated **up the tube**.

Let us say that this real image is formed $7\frac{1}{2}$ inches above the upper nodal point of the objective, or practically, $7\frac{1}{2}$ inches above the objective itself, while the true Focal Length of the objective is say 0·07575 inch. Then the object will be at 0·075 inch, nearly, from the lower nodal point of the objective, or practically, from the lower or anterior face of the front lens. Suppose the object examined to have a diameter of $\frac{1}{200}$ inch; the real image formed up the tube is **larger** in the ratio $d' : d$, or 7·5 : 0·075, or 100 : 1, linearly, and is therefore half an inch in diameter; so that the Magnification of this real image then has a value of 100, the Real Image actually having 100 times the diameter of the Object.

This **real image** may be **seen** on removing the eye-piece and looking down the tube from a distance; and it may also be rendered visible by letting down a little disc of tissue paper into the tube until the paper, acting as a **screen**, coincides with it.

The **real image** produced by the objective is itself treated, in the complete microscope, as the **object** of the Ramsden **eye-piece**. This eye-piece is a convergent combination adjusted so that the real image which is to be inspected lies **within its focus**, and forms a **virtual image at 10 inches** distance from the upper nodal point of the eye-piece, or practically at 10 inches from the Eye.

If the real image be at $2\frac{1}{2}$ inches from the eye, the virtual image at 10 inches from the eye is 4 times as large as the real image in the tube: and thus our instrument has produced an image (**virtual** and **inverted**), which is 400 times as large as the original object.

If, in the case supposed, an observer look down the microscope with one eye while with the other he looks at an inch **scale** laid down at 10 inches from the eye, he will see the image of the object ($\frac{1}{200}$ inch) apparently coincide with two inches of the scale. If his object be itself a **micrometer-scale**, finely engraved on glass, he can thus ascertain the **magnify-**

ing power of his microscope; for if the image of $\frac{1}{200}$ inch coincides in this way with 2 inches of a scale, he knows that the magnifying power of the instrument is 400; and then, if any other object of unknown size give an image which coincides, with say half an inch on the scale laid down as before, he knows that the size of that object is $\frac{1}{800}$ inch linear. But the observer may be **short-sighted**; in that case a virtual image at 10 inches from his eye would not suit him. He will make it a virtual image at say 5 inches. This he does by racking down the microscope so as to throw the first real image farther up, nearer the eye-piece: then the eye-piece makes a virtual image also nearer the eye-piece, say at 5 inches from the eye. This virtual image is, nearly, half the size of the image produced by the former observer. If the short-sighted observer proceed to measure with a scale in the same way, he will find that in order to make the virtual image be at the same distance as the scale (so that there may be no **parallax**, or relative movement between the two, when he moves his head slightly from side to side), he must lay his scale not at 10 inches but at five inches from his eye; and he will then find that the image will apparently coincide only with about one inch of the scale; so that the **magnifying power** of the given microscope is **less** for him, being only about 200 instead of 400 as it is for the normal observer. Similarly, a **long-sighted** observer will work with images and scales at a distance greater than 10 inches; and for him the same microscope will have a **magnifying power greater** than 400. But in all these cases the **visual angle** under which the image is seen, and therefore the actual diameter of the image found on the retina, is approximately **the same**; for 1 inch at 5 inches distance, and 2 inches at 10 inches distance, subtend the same angle.

Even the **two eyes** of the same observer may be **unequal** in power. Therefore it is of advantage to make one and the same eye observe both the image and the scale. This is effected by means of a device called a **camera lucida**, which presents different forms, already described (p. 282).

To return to the Eye-piece. The **Ramsden eye-piece** consists of two equal plano-convex lenses with an intervening diaphragm, as in Fig. 223: it produces comparatively small distortion and is therefore well suited for micrometric work, while it has also a broad field of view: but the eye-piece which is generally preferred is the **Campani** or **Huyghenian**

Fig. 223.

eye-piece. In this there are **two lenses** at a distance from one another: the lower of these, B, is the **field-lens,** while the upper, A, is the **eye-lens.** The Real Image produced by the objective is thrown well up, so that in the absence of the eye-piece it would be formed actually outside the microscope-tube. The rays converging on their way to form this image are intercepted by the plano-convex field-lens B, and then more rapidly converge so as to form a **real image** above the **focus** of the smaller and more powerful plano-convex **eye-lens** A. At the level of this image a diaphragm D is fixed. The lens A, in its turn, makes a Virtual Image at an appropriate distance (10 inches) from the eye.

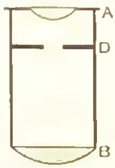

Fig. 224.

When we use a higher power eye-piece, the Focus of this is nearer to the eye; the Real Image to be inspected by the eye-piece must therefore be formed higher up the tube; and in order to bring this about, the microscope-tube must be racked down so as to make the objective approach the object.

In the **Ophthalmoscope** there is a **concave mirror** which reflects light from a lamp: this light converges upon and passes through a **focus** in front of the Eye observed: as it **diverges** from this focus it meets a **convergent lens,** which makes it **converge** on a focus **within** the media of the observed **eye** itself; and from this focus within the eye, the light diverges so as to **illuminate** the fundus or **back of the eye.** The back of the eye, being thus illuminated, radiates light: this light returns through the media of the eye, and on emergence therefrom it meets the convergent lens before mentioned, which forms a **real image** of the illuminated retina, **larger** in scale than the retina itself. This Real Image is **looked at** through an aperture in the mirror, and may be still further magnified by a second lens behind the mirror.

There is another ophthalmoscopic method, not so much used as the former. The mirror, with the aperture through it, remains as before; but it is so used as to illuminate the fundus of the observed eye directly. If the observed eye be normal and "accommodated for infinity," a cone of rays from any point of the retina to the pupil emerges as a parallel beam; and if the observer can deprive his eye of all accommodation, as if he were looking at an infinitely distant object, these rays come to a focus exactly upon his retina, and he sees an erect virtual enlarged image. But if the observed eye be too long in the bulb (myopic), or if the patient use his accommodation, the rays emerge from the observed eye not parallel but convergent; if it be too short (hypermetropic) they emerge divergent; and lenses may be needed to restore the rays to parallelism.

"**Focussing**" any **dioptric** or purely transparent apparatus, by **looking through** it, is very largely a question of the amount of **accommodation** exerted by the **eye of the observer.** Let the problem be to find out, by looking through it, what the proper position of the draw-tube of a **telescope** is, for distant objects. This is not so easily accomplished as might be expected. It will be found that as the tube is gradually lengthened, the **real image** formed by the objective is at first **very near** the eye-piece, and the rays from it are too divergent, so that the **virtual image** is **too near** the eye to be distinctly seen. But when the draw-tube is so far drawn out that the virtual image formed is at a distance of not less than 8 to 10 inches, the **eye** puts its **accommodation** to its **utmost strain**, and sees the image **distinctly**. As the draw-tube is still further extended, the image is **thrown** farther and farther **back**, and the **accommodation** of the eye is **relaxed**, but the image is still distinctly seen until the image is carried back to an **infinite distance.** Then the eye is at rest, using **no accommodation** at all. At that moment the Real Image formed by the object-glass is, as nearly as may be, at the **true focus** of the **eye-piece**, and the rays emerging from the eye-piece are parallel; but the observer would probably not reach this result unless he had trained himself to look through the apparatus in the same restful contemplative manner as one might look at the distant horizon. To be able to put one's **eyes at rest** in this way, in the use of dioptric apparatus, is an art which is worth acquiring by any one whose eyes are normal and who expects to have much to do with Lenses; and it is illustrated by what we have said about the Ophthalmoscope.

The **practical rule** for focussing a **telescope** would therefore be first to lengthen the instrument too much and then to shorten it until the image first comes distinctly into view as if at an infinite distance; and this is what people who use telescopes, opera-glasses, etc., usually do. The telescope only "brings distant objects near" when the tube is too much shortened down; and then it may bring the image of them even within a few inches of the eye; but this effect is due to the Eye itself being focussed upon a near point, and the Virtual Image being brought up to that point.

When a lens is used as a **magnifying glass**, the lens should be at first too far from the object, and should then be made to approach the object until the image first becomes distinctly visible, virtual at an infinite distance.

In the usual way of using the **microscope**, the tube of the instrument is racked up and then gradually lowered into position until the object comes distinctly into view, as a virtual image at an infinite distance. If the lens be first brought as near the cover-glass as is safe, and the tube then racked upwards, the object first comes distinctly into view as a virtual image at 10 inches distance. The accommodation of the eye is then strained to the utmost. The 10-inch method has, intrinsically, only the advantage of giving a standard for measurements of Linear Amplification; but as lenses are made, they are in fact **corrected** for this distance, or even, in many Continental lenses, for a still shorter distance of the virtual image.

A **short-sighted** person would not find the true Focus of a lens, or, generally, make the emergent rays parallel, in the way described. The distance which he would find would be such a distance as would cause the rays to enter his eye with a **divergence** corresponding to his own **greatest distance of distinct vision**, say 20 or 25 inches. If, however, he were provided with divergent **spectacles** which would give parallel rays this same degree of divergence, and thus extend his range of vision up to the **horizon**, he would then be in nearly the same position as a normal-sighted person. Similarly a long-sighted person, provided with the strongest convergent lenses which would still allow him to see very distant objects distinctly, would also be in the same position as a normal-sighted person.

Interference

Light is known to be a wave-motion, through the circumstance that it presents phenomena exactly corresponding to the mutual interference of Waves. When and where the crest of one wave exactly neutralises the trough of another wave crossing it, there is Rest: and we have, in Light, corresponding phenomena of darkness where Light-waves interfere with one another. This darkness may manifest itself in two ways: as actual Darkness at particular points; or by the absence or cutting out, at particular points, of particular components of white light, so that the remainder produces an impression of colour: and the phenomena attendant on Interference generally present a beautiful display of Colours, as for example, the colours seen on a soap-bubble shining in the sun.

Suppose a thin soap-bubble film AB, and suppose a ray of monochromatic light, light of one colour, of one wave-length, to strike it. Part of the light will be reflected at P and will travel towards T; part will be refracted towards P′ and will be there reflected and find its way out towards T. Now suppose that the whole path traversed by the light

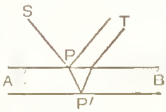

Fig. 225.

within the film is exactly one wave-length: the light reflected at P and the light reflected from P′ would then, we might expect, be in the same phase, both sets of waves being at crests and at troughs at the same time. But there comes in another circumstance, which is that the light, in undergoing reflexion at P′, at the surface of the less refracting medium, undergoes loss of half a wave-length. The proof of this proposition belongs to the Theory of Waves. The light-waves from P′ therefore, as they arrive at T, are in **opposition** to the light-waves coming from P: the crest of a reflected wave from P arrives simultaneously with the trough of a refracted and reflected wave from P′; and the Eye at T sees **no light**, for at T the resultant of the opposed waves is Rest. So for light of some one Colour, with a corresponding definite wave-length: but if the light incident at P be **mixed** white light, the other components will not be entirely cut out, though some of them will be weakened: and the Eye at T will perceive some Light, but this will be **coloured**, on account of the subtraction of the particular coloured-light which has been eliminated by Interference. With some other thickness of film, the light which will be cut out will have some different wave-length and colour: and with different obliquities of the incident ray, similar results will follow. This accounts for the play of colours on oil upon the surface of water, on films of iron oxide, on steel, on soap-bubbles, etc. If the film have a regularly **graded thickness**, as the thickness increases the wave-length of the light cut out goes on increasing along with it, and thus a sort of a **spectrum** may be produced. The film may be a film of **air**, as between a cover-glass and a microscopic slide squeezed together: in this case the loss of half a wave-length is at the upper, not at the lower boundary of the film. When a shallow lens is squeezed against glass, coloured spectra are produced which have a circular form, and are known as **Newton's Rings**.

If we fit a convex lens into the hollow of a concave lens, these Newton's rings will be observable at the **midpoint** if the convex lens have the sharper curvature, round the **edges** if it be the flatter of the two. When the curvatures are exactly the same, the Newton's rings **disappear**. These results are most readily attained in monochromatic light.

Fine grooving of a reflecting surface may produce analogous results; as in the **iridescence** of mother of pearl and of butterflies' wings or in the bands of cilia in Ctenophora; the light reflected from the **ridges** interferes with that reflected from the **grooves**, simply on account of its having travelled a shorter distance and being in advance of the other on arrival in the eye.

The **twinkling of stars** is due to this, that rays reaching different parts of the pupil of the eye, having come from what is practically a mere point through irregularly-refracting streaks of air (convection-currents, etc.) in the atmosphere, reach the eye in different phases. Now one colour is extinguished, now another. If a star be looked at with an **opera-glass**, and the opera-glass slightly but rapidly waved about, the image of the star appears spread out into a **many-coloured band**. If a **planet** be looked at in the same way, the image spreads out into a **plain** luminous band; for planets, having an appreciable disc, twinkle only at their edges.

That Light should **travel** in **straight lines**, as it does, is itself a consequence of Interference. At any point not in the straight course, the effects of the different parts of the wave-front are such as to neutralise one another; that is, provided the **breadth** of the wave-front is **great** in comparison with the **wave-length**. Objects of appreciable breadth will thus cast a fairly sharp **shadow** if the source of light be a **point**; but an absolutely sharp shadow is a thing unknown.

The projection of shadows on a screen from a minute source of light, such as the lime-light, or sunlight concentrated by a short-focus lens, is frequently of service in demonstrating the action of apparatus.

One consequence of the travel of Light in straight lines is that if a small hole, a **pinhole**, be made in a black card, a screen placed behind this card will have formed upon it a picture of external objects, as if the pinhole contained a **lens**; and if the distance between the card and the pinhole be sufficiently great, the image, though **dim**, is **as distinct** as that which can be produced by any lens. If the aperture be $\frac{1}{10}$ inch in diameter, this occurs at a minimum distance of 250 inches; but if, with that aperture, the distance be less, the

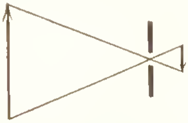

Fig. 226.

picture is blurred, since the aperture is not equivalent to a point. If the aperture be $\frac{1}{54}$ inch (No. 10 steel sewing-needle) the minimum distance is 8·51 inches (**pinhole photography**); but with apertures as small as this, or smaller, Diffraction-Fringes begin to confuse the result.

If the **source** of light be of some **breadth** there is a **penumbra** or fringe of half shadow round the full shadow formed upon a screen. From any point within this penumbra, a part of the source of light can be seen. If the source of light be a Point, there are very narrow **fringes** of alternate **light and darkness**, which blur the edge or boundary of the shadow formed. The production of these fringes is called **Diffraction**.

The sharply-defined edge of the wave-front, as it passes the obstacle, itself acts as a source of light: and the waves to which this gives rise alternately interfere with and help the wave-front itself: and thus there are formed fringes of alternate light and darkness. When the objects which form shadows are very small, and the source of light very minute, these **fringes** may **encroach on the shadow** so as to blur it altogether, and even to form a central spot or line of brightness at its centre. This may be seen by trying to cast the shadow of a **hair** from a source of light consisting merely of sunlight let through a small drop of glycerine in a minute hole in a card, or of electric light concentrated to a point in the focus of a high-power lens.

If the light employed be **mixed** or white light, each colour forms its own breadth of fringe, and the fringes are converted into **narrow spectra**.

Where we have light coming from a luminous point through a region containing numerous **small particles**, the image of the luminous point is surrounded by **coloured rings**, due to diffraction. We see this in the appearance of a distant lamp as seen through a **haze**, or through a window-pane gently breathed on, or through glass covered with lycopodium; or in the coloured rings seen round bright points in **glaucoma**, in which disease particles float in the vitreous humour of the eye. The **smaller** the particles, the **wider** the rings.

Where we have a **number of luminous points** at very **small distances** from one another, as in microscopical structures, diatom shells, and tissues, we find

Diffraction assume a most important bearing. The waves from the several luminous points interfere with one another and produce **Diffraction Spectra**. This is most distinctly seen in **diffraction-gratings**, which consist of plates of glass or metal ruled with very numerous grooves. Light is made to shine through or upon these gratings, and the transmitted or reflected light, if it be monochromatic, is sent in different directions after the manner of Fig. 70. If it be coloured, each component colour has slightly different paths. There is thus formed a succession of **spectra**. These spectra are very **pure**; and they are preferable to prism-spectra in respect that the **deviation** of each particular coloured-light depends, for any given grating, only on the **wave-length** (the sine of the angle of deflection being proportional to the number of grooves and to the wave-length only), instead of being also dependent upon specific anomalies associated with the particular kind of glass employed.

A microscopical preparation of **muscular tissue** will often be found to act as a more or less efficient diffraction-grating; the striations on the fibres take the place of the grooves engraved on the glass.

Diffraction is of great importance in the study of the behaviour of **microscopical objectives**; and attention to this has enabled them to be greatly improved during recent years. In Lenses, though it is convenient, and approximately correct, to say so, it **never** is truly the case that the **image of a point** is itself a **point**. It could only be a point if **the whole wave-system** originating in the object-point converged upon the image-point. In that case all lateral effects would mutually neutralise one another. But in the ordinary use of a Lens we have only a **portion** of the whole wave-motion **passed through** the lens; and the mutual neutralisation of lateral effects is incomplete. The result is that the **image** of a bright **point** is really a bright **disc**, brightest in the centre, fading away into darkness externally, and surrounded by concentric rings of alternate light and darkness, or by successive coloured annular spectra. The greater the proportion of the whole wave-motion which goes through the lens, the more nearly will the image of a bright point itself correspond to a bright point of light; and hence it is of importance to get the lens as near to the object as possible when we want excellence of definition of the image, or else—which is equivalent for this purpose—to use a lens in which the aperture is as wide as possible, or the diameter of the lens as great as may be, in proportion to the distance between the object and the front face of the lens.

In the object-lens of a microscope it is therefore of importance to bring the object as near the lens as possible, or otherwise to collect into the lens as wide as possible a bundle of rays from the object. When this is done there is undoubtedly a tendency to increase spherical and chromatic aberration, and thereby to impair the definition in the resulting image; but these aberrations can be got rid of by suitable correction. The importance of collecting a wide bundle of rays into the object-lens of the microscope is that we have to deal with very minute objects which may be considered as practically equivalent to points; then unless a large proportion of the whole wave-front be passed through the lens, the image produced by a minute object may be merely the product of a number of diffraction-fringes; and the result of the combination of such diffraction-fringes may be an image of some form quite different from that of the structure examined. When the breadth of the object is several times as great as a wave-length of light, the image will resemble the object in its form, for the object is in that case no longer comparable to a mere point: any diffraction-fringe waves which may be produced travel closely along with the direct image-forming waves: and in such cases a fairly narrow angle of aperture may suffice to admit the whole diffraction-fringe system, and thus to form an accurate image of the object, as in telescopes and opera-glasses. But when we have to do with finely-grained structures, the **diffraction-fringes spread out** at wider angles (Fig. 70), and it is necessary, in order to **get them in** to the lens and thus to enable an accurate image to be formed, to use a lens which presents a comparatively **wide** or extended **front** to the object. The image of a fine-grained object will always resemble the object more, the wider the angle under which the lens admits rays from any one point of the object: and the finer grained the structure, the wider should this angle be; that is, the greater should be the "Aperture" of the lens.

The "**aperture**" of a Lens is variously defined, to the confusion of the subject. In the first place let parallel rays in Fig. 227 be made, by the lens, to converge upon the focal point F; then the **ratio** between the **breadth** *aa'* of the parallel beam, or the diameter of the back-lens (as a numerator) and the **distance** LF between the front face of the lens and the focal point F (as the divisor) is the Aperture, according to one definition (i). Thus in a "$\frac{1}{2}$-inch objective" (an objective in which this distance OF is $\frac{1}{2}$-inch) whose back lens had a diameter of $\frac{1}{2}$ inch, the aperture would be 1·00.

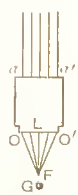

Fig. 227.

But a part of the diameter of the back lens might be ineffective: light entering it from behind might, by reason of diaphragms, mounting, etc., not reach F at all: or conversely, light radiating from F might fail to fill the apparent diameter of the back lens with light, and be confined to a central disc of say $\frac{1}{4}$-inch diameter. In that case the **effective aperture** (ii) would be $\frac{1}{4}/\frac{1}{2} = \frac{1}{2}$.

Then again, the Aperture of a lens has been defined as the ratio not for parallel rays but for such rays as traverse the lens during the **actual use** of the instrument (iii); that is the **ratio** between the **breadth** of the beam emergent at the back and the distance LG, when a bright point of light is situated at G; where G is the position occupied by an object in the ordinary use of the instrument.

Again, the Aperture, or the "**angular aperture**," is (iv) the number of **degrees of angle** between GO and GO′, where GO and GO′ are respectively the **extreme rays**, from the object G, that can find their way through the combination and out at the back lens.

In a simple lens all this is simplified by the circumstance that we have not to consider the front and back lenses of a combination, but only the front and back faces of the lens.

But during recent years there has arisen a new method (v) of specifying the Aperture of a microscopic objective, by stating its "**Numerical Aperture.**" In **air** this is the **ratio** between **half** the clear or effective **diameter** OO′ (as a numerator) and the **distance** GO or GO′ (as a divisor); that is it is equal to the *sine* of *half* the Angular Aperture OGO′, G being, as before, the position of the object. The greatest possible value that could be attained by the Angular Aperture OGO′ is 180° when the object G comes close up to the point C: therefore the greatest possible value of the angle OGL is 90°: and as the sine of 90° is 1, the greatest possible value of the Numerical Aperture, in air, would be 1.

In practice there is always some room required for the thickness of the cover-glass, and for the play necessary in focussing, so that the angular aperture cannot exceed 130°; and the sine of half 130°, or 65°, is 0·906, the practical maximum Numerical Aperture, in air.

Now let us suppose that the object G stands protected by a thin **cover-glass** C, and that the space between the cover-glass and the lens L is filled with **water**, W. The rays from G may be considered as meeting the cover-glass up to a maximum angle of 180°, or 90° on each side of the line GL. As they enter the cover-glass they will be refracted towards the line GL: but when they emerge from it they will not resume parallelism to their former course, but will travel, in the water, more nearly parallel to the line GL; and thus a **greater number of rays** will find their way **into the lens** when **water** occupies the space between the cover-glass and the lens than would do so when that space was occupied by free **air**.

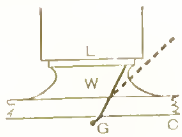

Fig. 228.

The **maximum angle** under which rays could enter the lens is, in water, about $83\frac{1}{2}°$; and the $180°$, in air, have been compressed into $83\frac{1}{2}$ in water. The relation between these angles is that $\sin(\frac{180°}{2}) = 1·5 \times \sin(\frac{1}{2} \times 83\frac{1}{2})°$, where the 1·5 is the refractive index of water. Generally, the **Numerical Aperture** is equal to $\beta \sin u$, where β is the index of refraction of the medium, and u is half the angle under which rays enter L.

The value of this arrangement, in so far merely as it serves for picking up a greater number of Rays from the object and sending them into the lens, is of merely secondary importance; a brighter illumination would produce the same effect. But it was early observed that when **wide-angle illumination** was used, the microscope showed **details of structure** better; and then, if the object were itself **immersed in water**, the resolution of details of structure was even better. This remained unexplained until Prof. Abbé took up the subject. He found the key to the secret; **we must get the spreading diffraction-fringes into the lens.**

Suppose we have a structure presenting finely-grained and regular markings, say a diffraction-grating; and let the lines on that diffraction-grating be n to the centimetre. If we take **any one point** in that object, any one line in that grating, as the thing which we desire to see distinctly or to **resolve**, and if we illuminate that point from behind, then we know that from any one point of such an object the various diffraction-spectra pertaining to that point are propagated along directions in space making certain angles δ', δ'', δ''', etc., with the axis of the illuminating beam. (See Fig. 70.)

These angles are such that $\sin \delta' = n\lambda$, $\sin \delta'' = 2n\lambda$, $\sin \delta''' =$

$3n\lambda$, and so on, where λ is the average wave-length of the light employed; and therefore the smaller the wave-length, the more closely are these diffraction fringes or spectra packed together.

But it will be observed that if the object be immersed in a medium of high refractive power, the wave-lengths are smaller in that medium than in air; and hence the diffraction fringes from each point of the object pursue courses which do not spread apart from one another as much as they do in air. Besides this, there are actually a greater number of these fringes within 180° in oil or water than there are in air.

In a medium of higher refractive power it is therefore easier to get one or more of these fringes into the lens than it is in air. In water or in oil they may meet and enter the lens, where in air they would pass outside it.

Then, if we take it that we cannot obtain any distinct resolution of detail at all unless we can get at least the first diffraction-fringe into the lens, we must get the object near enough to allow this first diffraction-fringe to enter the lens, and not to pass away outside it.

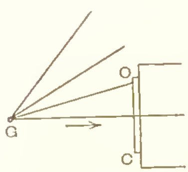

Fig. 229.

Ideally we ought to get them all in in order to form a true picture: but if we get none in, there may be no manifest relation between the form of a fine-grained object and that of its image. If we stop out some of the diffraction spectra which tend to be formed, we may obtain the most singular changes in the resultant image. We may see these diffraction spectra on looking down the tube of a microscope (the eye-piece being removed), under which an object with a very fine-grained pattern is being examined.

On looking at the equation $\sin\delta' = n\lambda$, for the direction taken by the first diffraction-fringe, we see that the distance of the object G must be such as to make the angle OGC not less than an angle whose sine shall be equal to $n\lambda$.

If, on the other hand, the medium be water, whose refractive index is $\frac{4}{3}$, the distance may be increased so that $OG' = \frac{4}{3}OG$, and yet the first diffraction-fringe will still enter the lens. This is because the wave-length λ is smaller in water: therefore the product $n\lambda$ is smaller: therefore $\sin\delta'$ is smaller, and the minimum permissible angle δ' is a smaller angle, so that G′ may be farther away than G.

In oil, which has a still higher refractive index than water, the permissible angle is a still smaller one, so that the object may be still farther off, and yet be equally well defined.

If now we make the object approach the lens, we find that we have passed beyond the conditions which are at all possible in any lens working in air. The utmost that a given air-lens can do is to show markings distinctly when their number, n per cm., is equal (in consequence of the equation $\sin \delta' = n\lambda$) to $\sin \delta'/\lambda$, where δ' is half the actual angle of aperture. Thus suppose the light employed has a wave-length $\lambda = \frac{1}{20000}$ cm. in air, and that the angular aperture, or angle OGO′, is 130°; then δ' is 65° and the sine of δ' is 0·906. Then the number of markings which can be resolved is $0·906 \div \frac{1}{20000} = 18120$ per cm., or about 46000 to the inch.

In a denser medium, the wave-length is shorter than in air; it is $\lambda' = \lambda/\beta$, where β is the refractive index of the medium. Hence if we use an oil-lens under a given actual angular aperture 2δ, the number of markings which can be seen is $n' = \sin \delta./\lambda' = \beta \sin \delta./\lambda$, where λ is the wave-length, for the particular kind of light, in air. Suppose again that the light employed has a wave-length $\lambda = \frac{1}{20000}$ cm. in air, and that the actual angular aperture is 130°, while the index of refraction of the oil is 1·515 (cedar-oil); then the number of markings per cm. which can be distinctly seen is $n' = 1·515 \times 0·906 \div \frac{1}{20000} =$ 27,452 to the cm., or 69,730 to the inch.

If the wave-length be diminished otherwise than by using a medium of high refractive power; if, for instance, we use only violet light of a wave-length of $\frac{1}{25000}$ cm., we still farther increase the value of n'. Hence by photography with ultra-violet rays we may resolve details which the eye cannot master. There is even a considerable gain in the use of blue light, such as that filtered through a solution of ammonio-sulphate of copper, or better, through a number of different samples of blue glass.

These numbers are, however, somewhat exaggerated, for they correspond to the markings for which the first diffraction-fringe can be got into the lens; but for good resolution a greater number of diffraction-fringes than this must be got in. The ideal true picture could only be secured by getting them all in. We can get the second fringe in to the lens if the number n be halved: the third if it be divided by three, and so on.

The value of n' may be made to rise so high that the product $n'\lambda$ may be greater than 1·00; and there is no possible angle δ' whose sine could have such a value. Hence the oil-lens may correspond to an air-lens with an impossibly wide angle of aperture, exceeding 180°.

The product $n'\lambda = \beta n\lambda = \beta \sin \delta'$, where the actual angular aperture is $2\delta'$; and this product, $\beta \sin \delta'$, is what is known as the Numerical Aperture, it being understood, as before, that the angular aperture $2\delta'$ shall be just that which is requisite, and no more, to let the first fringe or spectrum into the lens. In air, $\beta=1$, and the Numerical Aperture is equal to $\sin\delta'$ simply.

The name Numerical Aperture seems to be somewhat confusing, since the value of the expression $\beta\sin\delta'$ depends not only upon the actual Angular Aperture $2\delta'$ but also upon the Refractive Index of the liquid employed, or directed to be employed, with the particular objective; and the product $n'\lambda=\beta\sin\delta'$ is essentially a measure of resolving power rather than of actual Aperture.

If the medium between the lens and the object, the cover-glass, and the lens, all have the same index of refraction (say 1·515, the liquid being cedar-oil), we have a Homogeneous Immersion System, in which a grained structure can be resolved when its markings are more numerous (say 1·515 times as numerous in the case supposed) than those which can be resolved with a lens working under the same actual angular aperture in air.

Zeiss's objectives are now made with a front lens of flint glass of $\beta=1·72$; and the liquid used is monobromide of naphthalene ($\beta=1·658$). Hence the practical Numerical Aperture is as high as 1·63: and such lenses can resolve details which no air-lens, and even no oil-immersion lens, could grapple with.

Such oil-lenses also present some other advantages. For any given quantity of light, the course of the rays being more direct, less light is lost by reflexion at the first face of the lens. Again, the index of refraction of the cover-glass being the same as, or more nearly the same as, that of the general medium in which the rays travel, it matters nothing or comparatively little whether there be a cover-glass or not, in this sense, that the introduction or the absence of a cover-glass does not so much affect the existing correction for Spherical Aberration; and this renders the collar-correction (Fig. 217) a matter of less importance than it is in lenses which work in air. And for a given Magnification there is a greater working distance between the object and the lens than there is when ordinary lenses are employed.

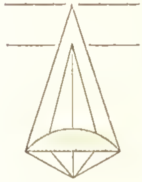
Fig. 230.

From the point of view of Diffraction, the over-correction or under-correction of a lens for spherical aberration is also of importance. If an over-corrected lens be used, the second diffraction-fringes, entering the lens at its periphery, do not come to the same focus as the first fringe and the direct rays from the object, but come to a focus higher up than the image of the object and first fringes: and they tend to produce a ghostly image situated in a plane above the real image of the object and showing, when thus isolated, twice as many markings as there are in the object. If an under-corrected lens be used, the second fringes tend to form a similar image lying below the image of the object.

The **measurement of the angle of aperture** of a lens or combination of lenses, in air, depends on the application of Fig. 231. Here parallel rays are brought to a focus at F and then diverge; the distance between F the focus and L the front of the front lens is supposed to have been ascertained. Then a **disc of light** is formed at D: and the diameter of the disc, together with the known distance DF, affords the necessary data for finding the **angle OFO′**.

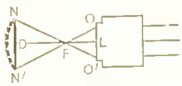

Fig. 231.

Or conversely, the light may travel in the opposite direction; and a diaphragm at D may be opened or closed or moved towards or away from the lens, until the **cone of light** NFN′, from an open sky, is such as to fill the **back of the lens** with light as far as it will fill.

Or again, the apparatus may be **rotated** back-and-fore round F until a distant small source of light fails, on one side and the other, to send any light through the instrument.

For immersion-lenses, the medium between L and D may be made to consist wholly of flint-glass, with the appropriate liquid between it and the lens: then a pair of pointers moved out to N and N′ will indicate the limits of the field of light, and these may, as in **Abbé's apertometer**, have their position ascertainable by means of an engraved scale along which they are slid.

Wide-angle microscopical objectives are thus favourable to **resolution of detail**; but **not** to **depth of focus**, for they can only grasp one plane at a time. In order to secure Depth of Focus, the angular aperture must be comparatively small, and the distance between the lens and the object correspondingly great. As the powers increase, the depth of focus falls off with extreme rapidity; and with high powers, the slice or section of the object which is in focus is an excessively thin one. The power of **looking into** the object along the line of sight seems to depend on two things: (1) the **accommodation** of the Eye, which acts like an additional lens or rather series of lenses; but in relation to high powers the effect of this becomes insignificant: and (2) the circumstance that the Eye is **not sensitive** to a moderate degree of **blurring**, for it is itself incapable of resolving detail presented to it under a less angle than from 1 to 5 minutes of arc; and consequently the image is no worse for being blurred to that extent.

Since it is necessary, in order to secure definition of extremely fine detail with a microscopic objective, to use wide angles in this way, it follows that if a **real image** of a fine structure be made by a **low-power** or narrow-angle objective, **no amount of amplification** of the image, by high-power eye-pieces or projection on a screen or otherwise, will **show the detail** which a wide-angle lens can reveal. Such an image can only show the general contours of the object, not the details of its structure, which may in many cases give no evidence whatever of their existence. On the other hand, when an object has not a finely-detailed structure, narrow-angle lenses are of advantage in respect that in virtue of their depth of focus, they show the mutual relation of the various parts of the object better than wide-angle lenses can do.

It is by means of Interference-Fringes that we are able to **measure** the **length** of the **waves** of Light. By a glass **biprism**, B in Fig. 232, whose angle is very nearly 180°, light from a point S will be refracted so that it travels *as if* it had come from **two sources** S′ and S″. The source S itself may be the Focus of a Lens through which a beam of light is passed, this light having been rendered approximately monochromatic by absorption. If a screen, or the observer's eye, be placed in front of the biprism, at N (Fig. 233), a series

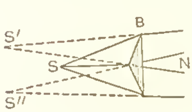

Fig. 232.

of alternating dark and bright **fringes** will be seen. The breadth of these fringes can be measured on the screen, and at N the two apparent sources can be seen and their apparent angular distance, the angle S′NS″, measured. The tangent of half this angle can be found in trigonometrical tables, and the **wave-length** is then equal to one **fringe-breadth** multiplied by **twice** that **tangent**.

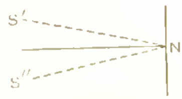

Fig. 233.

Suppose the biprism gives the apparent images S′ and S″ an angular distance of 17′20″; half this is 8′40″: the tangent of this is 0·0025; if there are on the screen 100 fringes to the cm., the wave-length is $0{\cdot}0025 \times 2 \times \frac{1}{100} = \frac{1}{20,000}$ cm.; and then, as the velocity of light is, in round numbers, 30000,000000 cm. per second, the frequency of the undulation (the product of the velocity into the wave-length), or the number of waves per second, is $30000,000000 \div \frac{1}{20,000} = 600,000000,000000$. This gives an idea of the methods by which these apparently incredible numerical data are ascertained.

Double Refraction

The study of Double Refraction is one which presents considerable difficulty: but the results of double refraction are of importance. Crystals have some kind of molecular grain or directed structure which makes light-vibrations, in particular directions, travel through a crystal with **different velocities in different directions.**

There is generally a particular Axis or direction in the crystal called the **principal axis**; and a slice of the crystal, cut with its face **parallel** to this principal axis, is said to have been cut in a **principal section**. In a crystal of Iceland spar this axis joins the opposite obtuse angles (Fig. 234).

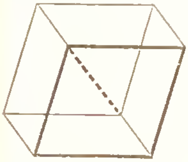
Fig. 234.

If a slice of Iceland spar be cut at right angles to this principal axis, and if light be sent straight through this slice, it will travel as if the crystal were ordinary glass: but in no other position will it do so. In every other direction of incidence and in every other mode of cutting the crystal, the incident ray is **broken up into two.** The result may be seen on looking through a crystal of Iceland spar at a page of print; every character on the page appears doubled.

The two rays into which an incident ray is split up are called the **Ordinary** Ray and the **Extraordinary** Ray.

The **Ordinary** Ray travels in Iceland spar much as ordinary light does in glass: the wave-front from any point of disturbance within the crystal is **spherical**: and the light obeys the ordinary laws of Refraction. It is to be noted, however, that if we find the plane in which the incident ray and the crystalline axis both lie, the ordinary ray is **polarised** in that plane: that is, its vibrations are restricted to directions at right angles to that plane.

The **Extraordinary** Ray has a more complicated behaviour, which we need not follow up: its wave-front is **ellipsoidal**: but the important point, for us, is that it also is **polarised** in a plane at right angles (or nearly at right angles) to that in which the ordinary ray is polarised; that is, its vibrations are restricted to directions parallel to the plane containing both the incident ray and the crystalline axis.

This division into two rays, both of which are polarised, has been utilised in the production of **polarised light.** There are various devices for this, of which it may suffice to mention **Nicol's Prism**, Fig. 235. In this the incident common light enters a long rhomb of Iceland spar at A and is divided into two rays. The crystal is cut across and re-cemented by Canada balsam at B, at such an angle that the **ordinary** ray is **totally reflected away** when it meets the cemented surface, while the Extraordinary ray goes on through the remainder of the Iceland spar. The face at which it

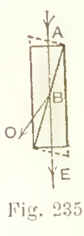

Fig. 235.

leaves is cut to such an angle that the emergent light runs parallel to the incident beam. The **emergent light**, the Extraordinary ray, is therefore **polarised.**

If plane-polarised light be run through a Nicol's prism, and if the prism be **rotated** round a **longitudinal axis,** in a certain position the light will come through, as through a **transparent** body. In rotational positions of the prism at **right angles** to this, **no light** will be transmitted. In intermediate positions some will pass through and some will be turned back.

In the most favourable position, the incident plane-polarised light acts, relatively to the crystal, as an Extraordinary ray and is let through. In the most unfavourable position, it acts as an Ordinary ray and is turned aside. In intermediate positions it is broken up into an Ordinary and an Extraordinary ray, of which the one is transmitted while the other is turned aside.

A **Nicol's prism** is therefore a means of **detecting** plane-polarised light as well as of **producing it**; for in the proper position it is quite **opaque** to plane-polarised light.

If the light be **partially** or **elliptically** polarised, the light transmitted will **wax and wane** as the prism is turned, but will not be extinguished in any position. If the light be **circularly**-polarised, or if it be **common** or natural light, the light transmitted remains **the same** in brightness into whatever position the prism be turned.

A pair of Nicol prisms may thus be used, the one to produce, the other to detect polarised light; and when the two prisms are turned into positions at right angles to one another, no light comes through.

If the prisms be placed so that **no light** can come through; and if a thin **film of mica** or other **doubly-refracting** substance, of uniform thickness, be caused to intervene between them, the **field** may become **filled with light,** coloured or white according to the position of the interposed film.

The explanation of this may be divided into two stages.

Let us suppose the light which has come through the first prism, the **Polariser**, to be polarised in a **vertical** plane: the only light which could come through the second prism, the **Analyser**, would be light polarised in a Horizontal plane; but there is no light polarised in a horizontal plane, seeking transmission; therefore **none comes through.** But if a **film of mica** be interposed, with its principal axis **oblique** to the vertical or to the horizontal plane, it acts as an ordinary double-refracting substance; and within its own substance it breaks up the vertical-plane light into an **ordinary** and an **extra-ordinary** ray. If these two rays had travelled through the mica-film at the same rate, the interposition of that film would have produced no effect, for these two rays would be again compounded, on emergence from the film, into a plane polarised ray the same as that which leaves the polariser; but they **do not travel at the same rate.** One or the other, according to the nature of the crystal, is **retarded** more than the other; and this difference gives rise to a condition either of **elliptical** or of **circular polarisation** in the light which has come through the mica-film. When the **analyser** now comes to deal with this, it **splits** it into **two rays**, of which it **transmits one**: and thus some light now comes through the whole apparatus.

Secondly, in this operation **each coloured-light** acts **independently**, and each is acted upon to a different extent by the mica film. Each emerges from the mica film in a different state of Elliptical or Circular Polarisation; and each is therefore differently represented in the final Ordinary and Extraordinary rays respectively. The natural consequence of this is, that the various colours are extinguished to different extents, and the light which comes through is not white but **coloured**, except in particular positions of the mica.

When the interposed film is of **varied thickness**, the field is filled with **variously coloured** light; and if it be of graded thickness, a kind of a Spectrum is seen.

The **doubly-refracting power** of a body may thus be detected when it is placed between **crossed prisms**.

For example, we know by this means that the **dim bands of muscle fibre** are doubly-refracting or "anisotropic." **Glass** becomes doubly-refracting on being compressed or twisted or stretched. Different **starches** present characteristic appearances, due to a quasi-crystalline structure.

Rotatory Polarisation is a name given to the **rotation** of the **plane** of Plane-Polarised light by certain substances such as Quartz; the light of **each colour** to **a different extent.** If quartz be used between crossed Nicols, should any kind of coloured-light, originally forming part of the incident natural white light, happen to have its plane rotated into parallelism with the principal section of the Analyser, then that kind of coloured-light is cut off: and the light which comes through is therefore **coloured,** by reason of this **cut-out.** Each position of the Analyser cuts out a **different colour.**

A piece of quartz 1 mm. thick rotates the plane of polarisation of a plane-polarised beam of yellow light through about 22°; and the direction in which it does so is towards the right, that is in the same direction as the hands of a watch, when the ray is looked at from behind, from polariser towards analyser. Quartz is therefore said to be **dextro-rotatory**; but there are samples of quartz which have an opposite effect, rotating the plane towards the left; and such samples are said to be **lævo-rotatory.** Cane-sugar and grape-sugar, in solution, are dextro-rotatory; fruit-sugar, starch, and albumen are lævo-rotatory.

The fortunate circumstance that the **rotatory dispersion** (the difference between the amounts of rotation for the different Colours) produced by **quartz** is the same as that for **cane-sugar** and **glycose,** enables the strength of solutions of sugars to be approximately determined by means of a **Saccharimeter.**

A **Soleil's saccharimeter** is made up of the following parts:—

(1) A **Nicol's prism,** achromatised; this **polarises** incident white light in a **vertical** plane.

(2) A **Biquartz**: this is a disc of quartz, made up of two semicircular halves, of equal thickness and of equal but opposite rotatory powers. Their thickness is so adjusted that they **rotate** the Plane of Polarisation of incident greenish-yellow plane-polarised light through 90°, in opposite directions: other colours more, others less. After transmission, the greenish-yellow component of the incident plane-polarised white light is **polarised** in a **horizontal** plane.

(3) A **Liquid-holder,** a tube or vessel to hold a thickness of 10 cm. of the liquid to be examined.

(4) **A Compensator.** This is practically a slab of quartz of adjustable thickness. There are **two wedges** of quartz, of which one can be slipped over the other more or less, and the central thickness thus regulated. The amount of movement is controlled by a Screw and measured by a Vernier and Scale. When the zero of the vernier coincides with the zero of the scale, the thickness of the quartz is just such as to rotate the plane of polarisation of the same greenish-yellow light through 90°; and in doing this it **undoes** the effect of one-half while it **doubles** that of the other half of the biquartz, No. 2. But in both cases it brings the Plane of Polarisation of that greenish-yellow light back to the **vertical.**

(5) An **Analyser,** generally a Nicol's prism.

(6) A **Lens,** to make a distinct image of the biquartz.

We fill the liquid-holder with water; we set the vernier to zero; we focus the lens on the biquartz; and then we turn the analyser round until a particular colour, between red and blue and rapidly shading off into either, comes to fill the field. The appearance of that colour shows that the analyser is then parallel to the plane of the greenish-yellow light, for it then cuts that colour out of the incident white light. **Both halves** of the biquartz then appear of the **same colour.**

If now we replace the water by the liquid to be tested, the two halves of the biquartz cease to appear of the same colour: then we **alter the thickness** of the Compensator until they do. If the compensator have to be thinned, its effect is the same as that of the liquid tested; if it have to be thickened, its effect is opposite; and therefore we must know beforehand whether the compensator is made of lævo-rotatory or of dextro-rotatory quartz. This we may find out by using it with a solution of cane-sugar, which is known to be dextro-rotatory.

The instrument is usually so made that each step on the scale amounts to $\frac{1}{10}$ mm. in change of thickness of the quartz of the compensator; and with the aid of the vernier we may read to $\frac{1}{100}$ mm. A thickness of 10 cm. of water, containing 1 grm. of diabetic sugar per litre, is equivalent to a thickness of 0·342 mm. of right-handed quartz or to 3·42 steps on the scale, and so on, approximately in direct proportion; so that if the thickness of the compensator have to be diminished by say 10·26 steps on the scale, this shows that the solution of diabetic sugar contains $\frac{10 \cdot 26}{3 \cdot 42} = 3$ grms. per litre.

CHAPTER VIII

ELECTRICITY

The subject of Electricity has been described as one in which it is not possible to understand the simplest experiment without understanding the whole subject: and to this it may be added that the whole subject cannot even yet be said to be itself clearly understood. Then, more than this, the language of modern Electricity is based upon a reasoned and systematic way of looking at the subject from the point of view of precise **measurement** of Electric Forces. The results obtained in this department of Physics cannot be properly appreciated without having followed up a train of reasoning somewhat mathematical in its character. On the other hand, the facts with which it is of importance that the Student of Medicine should be acquainted may be set before him in a fairly simple manner, provided that the author be allowed to omit here and there the explanation of the phenomena under discussion, or of the origin of the modes of expression employed.

Let the student, then, possess himself of a **galvanic cell** of any kind. The kinds which he will be most likely to meet with are those known as **Daniell's** (after Prof. J. F. Daniell of King's College, London), **Grove's** or **Bunsen's**, the **Leclanché**, or the **bichromate** cell. All these will be described presently.

It may, however, first be pointed out that none of these is really as simple as the earliest form of Galvanic Cell, namely, a piece of **copper** and a piece of **zinc**, both **in acid** (say dilute hydrochloric acid) and **not in contact** with one another (Fig. 236); or a disc of copper and a disc of zinc separated by a piece of wet cloth or of damp paper.

Fig. 236.

Let us first consider, then, the simple form of cell shown in Fig. 236. A good form of such a simple cell may be made with a tin can, filled with a solution of caustic soda, in which a rod or plate of zinc is partly immersed, but is not permitted to touch the tin can. In this the tin can itself corresponds to and replaces the copper plate of Fig. 236. If the **zinc** be chemically **pure** or if it be **amalgamated** with mercury,* the zinc will not be attacked by the liquid; but ordinary commercial zinc will be attacked and dissolved.

The cell, if once put up as described, will appear to be **at rest**, and so it is; it will appear to present no phenomenon worth note. This is, however, not the case; for **between** the parts of the **two metals** which stand **outside the liquid** there is a condition of affairs which in kind is **the same** as that existing during a thunderstorm **between** the **thunder-cloud** and the **earth**, but which in degree differs enormously therefrom. Between a thunder-cloud and the earth there is some kind of a prodigious **stress**, and the lightning discharge may partially relieve this stress by means of a **spark** tearing through a mile or more of air: between the two opposed metallic surfaces of our simple cell there is a similar stress and tendency to the production of sparks,

* By washing the zinc with dilute sulphuric acid (1 in 12); pour half a fluid ounce or so of mercury into the dilute acid; lower the zinc into the mercury and rub the mercury in with a rag. Or make an acid solution of mercury by putting $\frac{1}{4}$ lb. mercury into $\frac{1}{2}$ lb. nitric and 1 lb. hydrochloric acid; when the mercury is dissolved add $1\frac{1}{2}$ lb. hydrochloric acid; immerse the zinc in this solution for a few seconds: wash and rub it: it will be found amalgamated.

but this is so slight that it is difficult even to detect the tendency. Bear in mind, however, that the difference is one of **degree** not of **kind**. Even with such a cell as we have described, the student may be able to satisfy himself in a dark room that on bringing the two metals, the copper and the zinc or the tin and the zinc, in contact with one another outside the liquid, there are **minute sparks** produced on making and on breaking contact, particularly the latter.

Now let us turn to the other kinds of cells referred to above. First let us take the **bichromate** cell. This is diagrammatically represented in Fig. 237. Instead of zinc and copper we have **zinc** and **carbon**. There are usually two plates of carbon, one on each side of a central zinc plate, but these are connected together so as practically to form one carbon. The zinc and carbon plates are immersed in a liquid made of bichromate of potash and dilute sulphuric acid ;* and the cell is generally made in the form of a flask, with provision for lifting the zinc out of the liquid when the cell is not in use. The **Leclanché** cell is made up by putting a cylinder of sheet zinc into a glass jar, fixing up in the axis of the jar a solid rod consisting of a mixture of powdered gas coke, black oxide of manganese, and shellac, and filling up with a solution of chloride of ammonium.

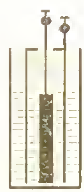
Fig. 237.

Sometimes, and specially in cells of very small size used for medical work, a **wet mass** of chloride of silver or of subsulphate of mercury is used between the two plates (**zinc** and **silver**), instead of any liquid.

Fig. 238.

The **Daniell** cell is more complicated in its structure. It presents externally a **copper cylinder**, which may stand within a glass jar (Fig. 238) or may itself form the walls of the containing jar ; then inside this a liquid (a saturated **solution**† **of sulphate of copper**) : then there is a **porous pot**, P, a pot of unglazed earthen-

* Bichromate of potash 1 part by weight, and hot water 18 by weight : allow to cool ; cautiously add 2 parts of sulphuric and ¼ part of nitric acid. Use when cold.

† This solution is kept saturated by means of some contrivance which suspends a quantity of sulphate-of-copper crystals in the upper part of the liquid.

ware which allows liquid to travel through its walls; then in this porous pot a quantity of dilute sulphuric acid; and lastly, in the very middle, a rod of zinc. In this cell the central zinc and the exterior copper play the same part as in Fig. 236; but the apparently more complicated arrangement presents advantages which we shall understand later on. In Grove's cell, we have an arrangement similar to Daniell's; but instead of putting the zinc centrally it is usually put externally, and instead of copper we have platinum; further, instead of a solution of sulphate of copper we have nitric acid. The arrangement is therefore, going from within outwards, platinum, nitric acid, porous pot, dilute sulphuric acid, zinc. In form Grove's cell is usually made flat and Daniell's cylindrical; but these forms may be exchanged without affecting the working, except in this respect, that porous pots are somewhat more fragile when made flat than when made cylindrical. In Bunsen's cell, the arrangement is practically the same as in Grove's, with this difference, that in the Bunsen carbon is used instead of the central platinum. In these forms the zinc always corresponds to the zinc of Fig. 236; the carbon or the platinum to the copper of that figure.

In all cases the zinc must be amalgamated, else it will be eaten away, even when the cell is not at work; and in all cases the zinc and the copper (or carbon or platinum) must be kept from direct contact or metallic communication with one another, else again the zinc will be eaten away by the liquid, even though amalgamated. Assuming however that these conditions are attended to, the cell will remain unchanged for a long time (evaporation being of course always provided for by the addition of water as required); and the copper and the zinc outside the liquid will continuously and constantly present a slight tendency to form a spark from the one to the other, but will at no time actually form such.

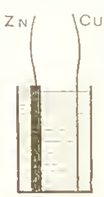

Fig. 239.

Now let us solder to the respective plates of a galvanic cell a couple of pieces of wire, which may both be of copper. Fig. 236 then would assume the form shown in Fig. 239. But this soldering is inconvenient: and in any actual cell the student will find that in connection with the zinc plate or rod there is a "**binding-screw**," which may assume various forms; and that similarly there is a binding-screw connected with the copper or carbon or platinum of the cell. This binding-screw serves to grasp tightly the end of a copper wire scraped bright and inserted into the aperture: the screw is turned down until the wire is held very tight. The **wire** must be **bright**, and so must the lower end of the **screw**: any dirt or oil or any film of oxide will interfere with the efficiency of the apparatus. If then a piece of wire be fitted to each binding-screw of the cell, the wires themselves become a kind of prolongation of the cell-plates: and if the **free ends of the wires** be brought near one another, it will be found that there is, between these free ends, a tendency to **spark**, and that sparks may be observed if the free ends are made to rub against one another in the dark, provided that the cells are large enough. Let us then lay the **free ends** of the wires very **near** to one another, but not so close that there is any actual sparking: and let us consider the state of things in the **space between** those free ends. There is across that space a condition of **stress** of some kind; and there is a tendency for this stress to become relieved and to disappear through the passage of a spark. How has this state of Stress arisen? It is not easy to answer the question: **energy** has been, at any rate, expended in setting it up. What is the source of that Energy? It is the energy of **combination** of a trifling amount of the zinc, which has been, as it were, burned up in the cell and dissolved in the liquid; but instead of its energy of combination being liberated as Heat (as it would have been if the zinc had been put alone into the acid) it appears as the energy of this stress, or the **energy of electric condition.** What is it, then, that is under stress between the free ends of the wire? To all seeming it is the **Ether**, the luminiferous Ether, of which we have spoken before. Clearly it is **not the air**, for the same conditions may be brought about in a vacuum. The Ether, therefore, is under stress; how it comes to be so is another question, to which there is as yet no answer. Allow however that it is so; then the **Ether**, being **elastic**, endeavours to discharge this stress and to return to its original condition. Between the two ends of the wires it is as if it had been **stretched**, or squeezed in from the sides: and the result of its **tendency to return** is that there is a tendency to draw the **free ends** of the wire **together**. This tendency is very small: and with thick wires it is not recognisable; but if very long slender strips of **gold leaf** be suspended upon the wires and made to approach one another, it will be found that these have a manifest tendency to **fly together**. We say then that the Ether succeeds in pulling them together; but we might also say, looking at what occurs, that the ends of the wires, or the two gold-leaf strips, **attract one another**: and this is the usual way of speaking on the matter. When we speak in this way we say that the two ends of the wires, or the two gold leaves, are in different Electric Conditions, and *therefore* tend to attract one another; but this does not really help us forward.

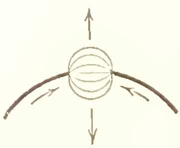

Fig. 240.

There are plenty of experiments, as we shall see farther on, in which this relative condition of two opposed bodies or points, or this stressed condition of the Ether between them, may be produced by other means than by chemical action: and the general rule is that once the opposed bodies are allowed to **touch one another** the stress may disappear and the difference between the electric conditions of the bodies may vanish. The electrical condition is then **discharged** or brought to nought, and the phenomena of Electricity disappear. A **galvanic cell**, on the other hand, is remarkable in respect that if we bring together the free ends of the wires from our cell, there is brought about a **continuous** peculiar condition of the whole space surrounding the wire and the cell. How is the Continuity of this condition maintained? One thing at any rate is clear, that it is kept up so long as **chemical action** in the cell is maintained, and no longer. When the zinc is all dissolved, or when the liquid in the cell can no longer act on the zinc, all phenomena due to this condition come to an end. We shall presently see what these phenomena are, but may before doing so note that they are in ordinary speech attributed to a **Current of Electricity.** In this view Electricity would be something which somehow passes along a wire as water passes along a pipe. But the phenomena attributed to a Current of Electricity are mainly phenomena in the **Field** or Region of Space **surrounding** the cell and wire; and it is now held that if we had a **perfectly conducting** wire "conveying a current of electricity," that **wire** would be the **only thing** in all the region which was **unaffected.**

Hence an apparent paradox; it is not the Atlantic cable but the Atlantic Ocean which conveys the Energy of a cable message; it is not any current of electricity along the electric mains which lights a town or drives tramway cars, but the transmission of Energy through the air, earth, buildings, etc., between the driving dynamo and the driven dynamo or the arc-lamps kept aglow. The reasons for this apparently singular conclusion are probably at present too recondite for the reader of this small volume: but there is now practically no difference of opinion among scientific men on this topic.

Let us return to our Cell and its terminal wires, and ascertain what the principal phenomena are which are observable in connection with these.

First let us keep the extremities of the terminal wires apart from one another. Then these wires are in different electrical conditions, and the wire connected with the **copper** is said to be "**positively** electrified" in comparison with the wire coming from the zinc; and the wire connected with the **zinc** is said to be **negatively** electrified in comparison with the wire coming from the copper. Let it be observed that this is a merely conventional use of terms: we might have reversed the nomenclature without doing any harm; but it has been agreed, in the practice of scientific men, to use these terms in this sense. Now let us connect these wires; phenomena are set up, mostly in the surrounding Field, which we are in the habit of attributing to a "current" of Electricity. But if Electricity is supposed to "flow," it is natural to say that when a path is provided for it, it flows from what is positively electrified to what is negatively electrified; and consequently our so-called Current is said to flow, along the wire be it remembered, from the (+) copper to the (−) zinc terminal of the cell. But further, it is said to flow in the liquid of the cell, from the zinc plate to the copper (or other) plate, and thus to perform a complete circuit. It is clear that the "current," whatever that may be, does exist in the liquid, for the liquid acts in relation to the surrounding region in exactly the same way as a portion of the wire would do if turned round so as to point in an opposite direction; and phenomena occur within the liquid which we shall consider presently.

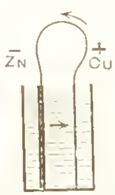

Fig. 241.

But in all this we must not forget the arbitrariness of our language: we do not know what flows; we do not know that anything flows; we do not know in what direction any Electricity flows, if there be any flow of Electricity at all. It is agreed to speak of the "current" as "flowing" in the directions specified; no more. The language used bears the impress of a time when Electricity was believed to be something which could flow, could be accumulated and condensed and so forth; and even now it is hardly possible to advance a step without making use of terms which imply some such conception. Let us then speak freely of a Current of Electricity flowing, and of its flowing in a particular direction along a wire, that is, from the

Copper (or carbon or platinum) terminal to the Zinc terminal of the battery or cell.

We may wish to **change the direction** in which the current is flowing in a given wire. We might effect this by disconnecting the wire from the battery and joining its ends up with the opposite terminals. But it is more convenient, usually, to use a **Commutator.** There are numerous forms of commutator; but we need only describe one of these. In Fig. 242, A is a brass plug connected by wire with the copper of the battery: B is another, connected with the zinc; C and D the same, connected with one another; and E is another. C and D have a binding screw G connected with them by a wire: E has another, F. Across from AB to CED there lies a pair of strips of metal, which can be rotated together round A and B so as to join AC and BE, or else to join AE and BD, at our pleasure. In the former case the current runs in the direction +ACDG-FEB−; in the latter it runs in the direction +AEF-GDB−. It will thus be seen that the direction of the current along the circuit wire between F and G is different in the two cases.

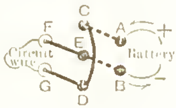

Fig. 242.

Whenever we have anything which is said to form a **current,** there must be room for Variations or Differences in the **rate of flow.** In the case of a current of Water we say that the current is one of so many gallons per minute, or of so many grammes or cubic centimetres per second; in the case of Electricity, a current which is twice as strong as another is said to be due to the passage or Flow of twice as many "**units of electricity**" per second. This is an expression which the reader will not at this stage understand; but he will find it again when we come to the phenomena of Electrostatics. For practical purposes he will, however, note that the practical Unit-strength of current is the strength of that "current" which is supposed to "flow" when the particular Unit of Electricity known as a "Coulomb" is supposed to take one second to pass any given point; the Practical Unit-Current is a current of one **Coulomb per second**; and such a current is known as a Current of one **Ampère.** But we may obtain an idea of the Ampère without troubling ourselves with the Coulomb. Let us take an ordinary average **pint Daniell cell** and connect its terminal binding screws by means of a **thick** piece of **wire**; the Current passing along that wire will have a strength equal to about ¼ **Ampère**. If we take **four such cells**, and if we first connect all the zincs together and all the coppers together by thick wires and then connect the conjoint zincs with the conjoint coppers by a thick wire, the current flowing along that thick wire will have a strength about equal to **one Ampère**. Thus **currents** vary in **strength**, and the strength may be measured in **Ampères**; the current which keeps an **arc-lamp** alight may be of say 60 Ampères: that which keeps a **galvanocautery wire** aglow may be of say 25 Ampères; that which passes through an **electric incandescent lamp** of 16 candle power may be one of, say, from ½ Ampère to 2 Ampères; the currents passed by the **medical man** through the human body may be say from 3 to 300 thousandths of an Ampère, or **milli-ampères**; the currents used by the **telegraphist** may have a strength of say one-sixtieth Ampère: and a current sufficient to work a **telephone** may be say one sixty-thousand-millionth of an Ampère. But these strengths are all inferred from the phenomena to which the current gives rise; the **strength** of a current, in Ampères, is measured by its **effects**.

The principal **Effects** of a Current are the following:

(*a*) Production of **Heat** in the circuit, always.
(*b*) Production of **Light**, in particular cases.
(*c*) **Electrolysis**.
(*d*) The production of a **Magnetic Field**:—

(1) The action of Currents upon Magnets.
(2) The action of Currents upon other Currents.
(3) The action of Currents upon Soft Iron.

(*e*) **Physiological Effects**.

(a) The Production of Heat by an Electric Current

Let us take a piece of very thin platinum wire, and let us connect this with the terminals of a cell or battery of cells: for example we may bring up a pair of thick copper wires from the cell or battery and make their free ends approach one another, and then lay our short piece of very thin platinum wire across these free ends. The little piece of platinum wire becomes **warm** or **hot**. It may become white-hot or may even melt. The **stronger** the current, the **hotter** the wire becomes: and for a given piece of such wire the law is that a current of **twice the strength** will produce **four times** as much Heat in that wire in a given time; one of three times the strength will produce nine times as much Heat; or generally, the **strength of the current** is proportional to the *square root* of the quantity of **heat** produced.

Suppose our little piece of platinum wire formed a small loop, projecting from the end of a rod of gutta-percha in which the two thick copper wires connected with the platinum wire and with the battery were separately embedded, and that the loop was dipped in **water** and the current passed. Heat would be developed in the wire as before, but it would be taken up by the water; the water would **rise in temperature**, and with a sufficient current might even be boiled by this means. The amount of Heat lost to the water might readily be measured by finding what its rise in temperature was: and the quantity of the water we are supposed to know: so that if we have say 60 grammes or 60 cub. cm. of water raised 5° C. in temperature by a given current in one minute, and raised 5° C. by another current in 4 minutes with the same apparatus, we know that the former current has twice the strength of the latter, because in a given time it produces four times as much Heat.

Fig. 243.

Of course for accurate work we would have to allow for the loss in both cases by Radiation of heat from the heated water; but we are not concerned with this at the present moment.

It will not be difficult to understand that if we can find means to **regulate** our **current** we can **regulate** the **temperature** we obtain in the thin wire, and that we can thus heat a spiral of platinum wire only just enough to hatch an egg round which it is placed, or enough to cook it; that we can heat a loop of platinum wire only enough to make it slowly char its way through a tissue round which it is placed and through which it is drawn, or can heat it sufficiently to make it rapidly cut its way through at a white heat; that we can heat a dome-shaped spiral of platinum wire to a dull-red heat, and apply it for checking the oozing of blood; that we can fell a tree by pulling through it a platinum wire kept aglow by a sufficient current. In all these cases the amount of Heat produced is proportional to the *square* of the Strength of the Current actually passing.

But one is apt to suppose, when one sees such a little loop or piece of wire at a red or white heat while the rest of the apparatus appears cool, that the Heat is only developed in that glowing bit of wire, and nowhere else. That would, however, be a mistake. It is a matter of proportion. **Heat is developed all round the circuit**; some—and this sometimes a very large proportion—in the battery cells themselves; some in the thick wire; some in the thin wire; but generally, the **worse as a conductor** any given part of the circuit may be, **the more heat** will be developed in that part. The thin piece of platinum wire is a bad conductor: it therefore grows comparatively hot. The thick copper wire is a good conductor: it therefore develops less heat.

In an **electric fuse** we have a worse-conducting part of the circuit made of fusible metal; when the current becomes excessive the heat developed melts the fuse, and the current ceases.

If there be any part of the circuit in which a **bad conductor** is interpolated, the **greater part** of the Heat developed in the whole circuit may under some conditions be developed there: never the whole of it, by any chance. Whenever, again, there is a **flaw** in the circuit, the conduction becomes bad at that point, and **heat is locally developed** when the current passes. Thus if in the wiring of a house for electric lighting there be a bad joint in the wires, or if the wire be worn away or gnawed away at any given point, there will be Heat developed to an undue extent at the flaw, and the temperature may rise at that point to such a height as to set the building on fire. Hence the need for a thorough belief in the danger of electric lighting rather than in its immunity from fire-risk; for it can only be safe if there are no flaws.

If a powerful electric current be passed directly from carbon or metal to the dry human skin, the skin may be burned and a slough formed. If it be led to the skin through a wire brush, and the skin brushed, a powerful tingling effect is produced.

We may make **artificial flaws** in a Circuit, and observe the heating which goes on. For example if we pass a strong current through two pieces of carbon in contact, they become hot, certainly, because they are bad conductors; but if we separate them a little or allow their contact to be very loose, we may see the **electric arc light** produced.

Again, if in a circuit we make such a flaw between two carbons (thus practically producing the arc-light) between two hollowed-out blocks of lime, which are non-conductors and prevent heat from escaping, we have the **Electric Furnace**. By this, with powerful currents, temperatures have been attained and chemical decompositions have been effected during recent years, which had previously not been thought possible. Again if we, still using powerful currents, pass the current through two masses of metal which touch one another by a **loose contact**, the point of contact is a place of bad conduction and becomes heated; but the hotter it gets the worse the conduction becomes, locally, for hot metal is a worse conductor than cold;

so that the two adjacent surfaces of the metal rapidly heat up; and by this means, by utilising the heat developed at the local flaw in the circuit, large masses of metal are now daily **welded together** in manufacturing industry.

It will be borne in mind that all this is a question of degree and of proportion: even a **flaw** must have some Conducting Power, else the current would stop altogether; but if it have any, then it acts as if it were **equivalent** to a **wire** of some ascertainable length and thickness, and of the same conducting power as the flaw.

In order to clear our ground, we must now devote some pages to a digression on the Conducting Power and the Resistance of a conductor, and shall return thereafter to the Heat developed in the circuit, generally or locally.

Resistance and Conductance.—In a flaw in the circuit, or in a very long thin platinum wire, the Conducting Power (or **conductance**) is very small: and this is otherwise expressed by saying that the **Resistance** of the flaw, or of the platinum wire, is very great.

If we had a wire of a **perfect conductor**, there would be **no resistance**, and **no heat** developed in the wire on the passage of the current; but there is no such thing as a perfect conductor, though some metals when excessively cold have marvellously small resistances.

It is necessary that we should have some **standard of comparison** of Conductances on the one hand or of Resistances on the other. The Standard Conductor would have **unit conductance** and therefore **unit resistance**: and it is a column of mercury 1 sq. mm. in cross-section and 106·3 cm. in length. The Conductance of such a Standard Conductor is said to be one Mho; and its **resistance** one **Ohm**.

It is more usual to specify the **Resistance** of a conductor in **Ohms** than it is to state its Conductance in Mhos. With regard to any particular conductor it is sufficient to know either of these, for the number of Ohms is the inverse of the number of Mhos: and thus a conductor whose conductance is 10 Mhos has a resistance of $\frac{1}{10}$ Ohm.

The Resistance of a conductor (of uniform diameter) varies *directly* as its **length** and *inversely* as its **cross-sectional area.**

A uniform column of mercury l cm. long and o sq. cm. in transverse section, has a resistance equal to $\{l/o \div 10630\}$ Ohms. Thus if it be 1 metre long ($l = 100$ cm.) and have a cross-area of $\frac{1}{2}$ sq. cm., its Resistance is $\{(100 \div \frac{1}{2}) \div 10630\} = \frac{200}{10630}$ Ohm.

The Resistance of a conductor also depends on its **material**, and is proportional for each substance to a particular number which has to be found by experiment and which is called the **resistivity** of the substance. The inverse of the Resistivity is called the **conductivity**.

Thus copper is a better conductor than mercury: under similar conditions a current passes through it 61·70 times as strong as will pass through mercury: its Conductivity is 61·70 times, and its Resistivity $\frac{1}{61 \cdot 70}$ times that of mercury.

It is more usual for us to find Tables of Conductivities than it is to find tables of Resistivities. Thus with regard to copper, for example, the usual datum would be that its Conductivity is 61·70; that of mercury being taken as unity.

Let us write the Conductivity as γ; then the Resistance of a uniform conductor of any substance is $\{l/o \div 10630\gamma\}$. For example, in **platinum** the Conductivity is 6·46; and the Resistance of a platinum wire 12 cm. long and $\frac{1}{2}$ mm. in thickness is $12/o \div (10630 \times 6 \cdot 46)$; then we must find o, which is $0 \cdot 7854 \times (0 \cdot 05 \text{ cm.})^2 = 0 \cdot 0019635$ sq. cm.; so that the Resistance is $\{(12 \div 0 \cdot 0019635) \div (10630 \times 6 \cdot 46)\}$ Ohms, or 0·089 Ohm.

The Conductivity of pure **water** is not greater than 0·000000,000025 times that of mercury. Hence a column of pure water, 1 metre in length ($l = 100$ cm.) and 1 sq. cm. in cross-section ($o = 1$), has a Resistance equal to $(l/o) \div (10630 \times 0 \cdot 000000,000025)$ Ohms, $= (100 \div 0 \cdot 000000,265750) = 376,319000$ Ohms, at least; and it is therefore practically a non-conductor. **Gutta-percha** offers a resistance far greater than even this.

From this we see that substances of the same size and form may differ very much in their power of conveying or conducting an electric current: some, as metals, allow it to pass with relatively little resistance: others offer much resistance, and their conductivity is accordingly small.

Hence a current passing along a wire sufficiently coated with **gutta-percha** may be prevented from escaping, and kept in its path; and in the natural electric currents found in a nerve of the body, the **neurilemma** and the **fatty medulla** of the nerve play the same part, in relation to the conductive axis-cylinder of each fibril, as the gutta-percha does towards the wire.

The **tissues of the body** are mostly very bad conductors and offer high resistances; for example, the eyeball presents a resistance of about 2500 Ohms, and an equal bulk of brain-substance about 1600. A pair of **needles** connected respectively with the terminals of a battery, and with their points apart, will, when inserted into the tissues of the body, give only an imperceptibly minute current: but if they come upon and enter a **bullet** lodged in the tissues, the current-strength goes up at once to a high value, and the current may be detected by any appropriate appliance, such as a galvanometer or a microphone.

The **human skin** when dry, or dried by drying-powder, is a particularly bad conductor; if it be **wetted** it conducts much better, and allows current to pass into the deeper structures.

We even find that **moist air** is a better conductor than dry air: so that the vapour arising from his body adds an element of danger to the position of a person in an exposed place during a thunderstorm, for that vapour affords an easier path for the spark.

Any **dust** or grease or rust about a galvanic cell or battery may, practically, wholly arrest the flow of current. Hence the importance of clean, unoxidised surfaces.

The Resistances which may be interposed between one point and another on a galvanic circuit, in order to moderate the current, will usually be found in a "**resistance-box.**" This consists of a series of **coils of wire** of known Resistance, measured in Ohms or decimal fractions of Ohms, which are fitted up in a box and so arranged that the current may be made to pass through them all, or through any desired number of them at will.

Each of these coils is made of insulated German-silver wire, or of an alloy of silver with 33·4 per cent of platinum. The resistance of these materials is found to vary extremely slightly with the changes of temperature to which the passage of the current gives rise. The two ends of each coil are fastened to massive copper rods, and the coil is imbedded in paraffin. In the ordinary state of the instrument these massive copper rods are connected to one another by a massive brass or copper **plug**, which "**short-circuits**" the coil; that is to say, it provides a path of immensely less resistance than the coil itself. When the **plug is taken out**, the current is obliged to pass through the corresponding coil, as at A, Fig. 244. By taking out the appropriate plugs we can, with properly varying values of the respective coils, give the total Resistance put into circuit a very large range of values, and thus modify the current-strength to any desired extent within the compass of the instrument.

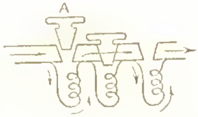

Fig. 244.

Wheatstone's Bridge is an instrument whereby the Resistance of any given conductor can be ascertained. In its simplest form it consists, as shown in Fig. 245, of a diamond of conductors AB, BC, CD, DA, a cross-conductor BD with a galvanometer G, and a connection AZnCuC in which there is a galvanic battery ZnCu. Observe the use of the **conventional sign** for a **galvanic battery** in the figure: the **short thick** lines stand for negative plates (*e.g.* **zinc**) the longer and thinner lines for positive (*e.g.* copper). The **galvanometer** needle is **at rest** when the **Resistances** in the respective arms of the diamond are in the **ratio** $R_{AB} : R_{BC} :: R_{AD} : R_{DC}$. Hence if we know two of the resistances, and have the means of adjusting the third to a known extent until there is **no current** through the **galvanometer**, we know the value of the fourth.

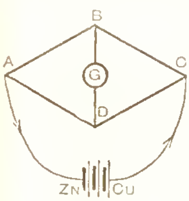

Fig. 245.

The required known adjustment of the third arm's resistance may be effected by means of a **Rheostat** or **Rheochord**. This consists of two cylinders: one of these, C, is metallic; the other, B, is non-conducting and bears a screw-thread. When the rheostat is intended to offer no resistance, the whole of the wire is rolled on to the metallic cylinder: the current then runs from A to the metallic cylinder C and on by D. As the cylinder B is rotated back, the wire is unwound on to the screw-threaded non-conducting cylinder B, and the current has to pass round the wire so wound upon B. The amount of this wire so wound on B may be ascertained from the number of revolutions of the cylinder. This is however a rough form of apparatus.

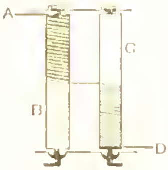

Fig. 246.

Another method is to vary AD and DC together by means of a **Sliding Contact.** The wire from the galvanometer is so fitted that it can slip along and touch any point D between A and C: then the resistances between A and B and between B and C being known, the same ratio AB : BC :: AD : AC still holds good in relation to the resistances. The objection to this form of instrument is that the sliding contact causes wear of the wires, and interferes with the accuracy of the results.

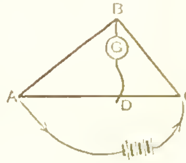

Fig. 247.

The use of **Resistance-boxes** is to be preferred to that of sliding contacts. If, in a resistance box the successive coils are at 5000, 2000, 1000, 1000, 500, 200, 100, 100, 50, 20, 10, 10, 5, 2, 2, 1 Ohms each, we can, by taking out the proper plugs, give the resistance of the box containing these 16 coils any value we please from 1 to 10,000 Ohms: and we may use such a box as the Resistance between say B and C.

But we may go farther. Instead of using resistances of fixed value in AB and AD, let us put resistance-boxes in these also. It will not be necessary for us to give these any other values than multiples of 10, say 10, 100, and 1000 Ohms each. Suppose then that the respective resistances of AB, AD, BC are 1000, 10, and 2784 Ohms when the unknown resistance stands between D and C and the galvanometer is at rest: what is the value of the unknown Resistance? AB : BC :: AD : DC; or 1000 : 2784 :: 10 : 27·84: whence the unknown resistance is 27·84 Ohms. We have thus taken our measurement down to two places of decimals, and extended the range of the instrument down to 0·01 Ohm. On the other hand, if BC be greater than 10000 when AB = AD, we then make $AB = \frac{1}{10}$ or $\frac{1}{100}$ AD, and thus extend the range of the instrument to 100,000 or to 1,000000 Ohms.

In practice these three resistance-boxes, AB, AD, and BC, are arranged on the same board, and provision is made for the insertion of the unknown Resistance between D and C;

and further, the battery stands between A and C, and the galvanometer between B and D, as in the diagram of Fig. 245. Fig. 247 shows how the respective Resistances are generally arranged when the Wheatstone's Bridge is made up with resistance-boxes in this way; and it will be found that this figure substantially agrees with Fig. 245. The resistance in any arm corresponds of course with the plugs which have been *taken out of* that arm.

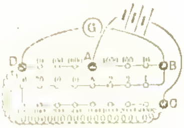

Fig. 248.

There is, however, another kind of resistance-box often to be met with in medical work, in which the plug has to be put in in order to determine the resistance, and in which no current runs unless the plug is in. The principle of this is illustrated by Fig. 249. The current comes in at the segment 0, and it has to go forward from the central metallic disc. Unless the plug is in somewhere in the circle, there can be no current, for there is then no communication between the segment 0 and the central disc: if it be in at the segment 0, there is no resistance: if it be in at the segment 1, the current has to traverse one of the coils connected with the numbered segments: if at the segment 2, two coils, and so on; so that the number of the segment indicates the number of coils traversed. If there are five such circles, bearing respectively 10000-Ohm, 1000-Ohm, 100-Ohm, 10-Ohm, and 1-Ohm coils, 9 to each, any number of Ohms can be promptly put in circuit, from 1 to 99999.

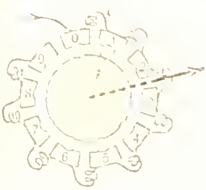
Fig. 249.

Sometimes very high Resistances are obtained by the use of rheostats of fluid or of graphite, or even of mere black-lead pencil lines on paper.

Branched Currents.—When a current is sent along a **branched wire**, as in Fig. 250, the current arriving at A is equal to the sum of the two currents leaving A by the two branches: and conversely, the currents arriving at B are together equal to the current leaving B. The strength of the current passing along ACB is to the strength of the current passing along ADB as the Conductance of ACB is to that of ADC; or otherwise, the **relative strengths** of the currents in

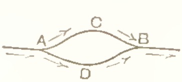

Fig. 250.

the branches are *inversely* **proportional** to their respective **resistances**.

For example, suppose we have a current of $2\frac{1}{2}$ Ampères going round the circuit; but in its way it finds a branched arrangement such as that of Fig. 250, in which the respective resistances of ACB and ADB are 8 Ohms and 2 Ohms. What are the respective currents in the two branches? Let i be the current-strength in the 8-Ohm branch and $(2\cdot5-i)$ the current-strength in the 2-Ohm branch; then $i:(2\cdot5-i)::\frac{1}{8}:\frac{1}{2}$; and on solving this simple equation we find $i=\frac{1}{2}$ Ampère in the 8-Ohm branch and $(2\cdot5-i)=2$ Ampères in the 2-Ohm branch.

Suppose we have to insert in the circuit a piece of apparatus which would be injured by the full current, we could divert any desired proportion of the current by sending a part of it along a branch or "**shunt**" of sufficient Conductance, that is, of sufficiently small Resistance.

Suppose we desired a current in ACB to be reduced to $\frac{1}{100}$, and that the resistance of ACB was as before, 8 Ohms: what must be the resistance of the additional path, that is, of the shunt ADB? We see that if $\frac{1}{100}$ of the current goes by ACB, $\frac{99}{100}$ must go by ADB: therefore the Conductance of ADB must be 99 times that of ACB: that is to say, the Resistance of ADB must be $\frac{1}{99}$ that of ACB, or $\frac{8}{99}$ Ohms.

In a **Du-Bois-Raymond key**, the current is practically shunted off from a nerve-preparation by being made to pass partly through a thick mass of brass: the share of the current which the nerve then gets is inappreciably small. When the key is opened, the nerve gets all the current which its resistance will allow to pass.

Currents travel wherever there is a **conducting path** for them; hence they affect the **more remote** parts of the body when applied superficially. For example, on electrifying the face, it may be that the optic nerve is irritated.

After this explanation as to Resistance and Conductivity we may return to the Heat generated in a circuit, or in any given portion of a circuit, on the passage of a current. This **Heat** is, *per second*, numerically equal to the **Ampères** *squared* × the **Ohms**; that is, on condition that it is itself measured, not in ergs, but in **Joules**, of 10,000000 ergs each.

Thus the Heat developed in a coil of wire, whose resistance is 12 Ohms, by a current of 7 Ampères is $(7^2 \times 12) = (49 \times 12) = 588$ Joules per second, or 5880,000000 ergs per second.

There is another mode of stating the same result which deserves attention. Suppose we have a conductor whose resistance is one Ohm and that the current passing is one of one Ampère: then the **conductor** is in **different electrical conditions** at its **two extremities**, for if it were in the same electrical condition at both ends no current would flow along it. This difference of condition is known as the **Difference of Potential**, and will be more fully explained later on; but it is analogous to a Difference of Temperature in the flow of Heat, or to a Difference of Pressure in the flow of a Liquid. In the case specified (one Ohm and one Ampère) the two ends of the conductor are said to be under a difference of potential (sometimes called an Electromotive Force or a **voltage**) of one **Volt**. The Ohm, the Ampère, and the Volt are thus closely related; and if any two of them be known with reference to any particular conductor or portion of the circuit, the value of the third may be readily inferred, for the three quantities are related thus:—**Volts = Ampères × Ohms**; or **Ampères = Volts ÷ Ohms**; or **Ohms = Volts ÷ Ampères.**

Thus if in a given coil whose Resistance is 12 Ohms there be a current passing whose strength is 7 Ampères, the Difference of Potential under which that current passes is 84 Volts: for 7 Amp. × 12 Ohms = 84 Volts.

The statement of this relation is the extremely important law known by the name of **Ohm's Law.**

The Heat produced is, therefore, in **Joules per second**, also equal to the **Volts × the Ampères**; and it is, further, equal to the **Volts** *squared* ÷ the **Ohms.**

Problems.—1. In an ordinary pint Daniell cell, the **difference of potential** between the two plates, when they are not brought into metallic communication with one another, is about one Volt. The resistance of the cell itself is usually about 4 Ohms; that is to say the cell itself is equivalent, as a conductor, to about 425·2 cm. of standard mercury-column. Now let us connect the copper and the zinc by a short thick bit of wire which offers practically no resistance to the flow of a current. A current then passes round the circuit; and its strength is Volts ÷ Ohms $= 1 \div 4 = \frac{1}{4}$ Ampère. Next let us find how much Heat is developed *per second* in the cell, when it is thus allowed to run to waste. This is (Ampères)^2 × Ohms $= (\frac{1}{4})^2 \times 4 = \frac{1}{4}$ Joule per second, or 2,500000 ergs per second. The same figure is reached by taking the Heat, in Joules per second, as Volts × Ampères $= 1 \times \frac{1}{4} = \frac{1}{4}$; or as (Volts)^2 ÷ Ohms $= 1 \div 4 = \frac{1}{4}$.

2. Next, let us put between the terminals a long coil of thin wire, whose Resistance is say 80 Ohms. The whole Resistance in the circuit is now 84 Ohms; and the Strength of the Current is, in Ampères, = Volts ÷ Ohms $= \frac{1}{84}$ Ampère. Now let us ascertain how much Heat is developed, first within the cell itself, and second in the long connecting wire. First, then, within the Cell: the current-strength is $\frac{1}{84}$ Ampère and the resistance of the cell is 4 Ohms; the Heat in the cell is therefore (Ampères)^2 × Ohms $= (\frac{1}{84})^2 \times 4 = \frac{1}{1764}$ Joule per second = 5669 ergs per second. Secondly, in the Wire; the current-strength is $\frac{1}{84}$ Ampère and the resistance of the wire is 80 Ohms; the Heat in the wire is therefore $(\frac{1}{84})^2 \times 80 = \frac{1}{88\cdot2}$ Joule per second = 113369 ergs per second.

3. What is the Difference of Potential between the two ends of the connecting wire in the last example? We know that Volts = Ampères × Ohms. The difference of potential in question is therefore $\frac{1}{84}$ Amp. × 80 Ohms $= \frac{80}{84} = \frac{20}{21}$ Volt. The whole of the potential-difference obtainable from the cell (one Volt) is not available for the service of the connecting wire, for a part of it is absorbed in driving the current through the cell itself.

4. In a Grove cell the internal Resistance, that of the cell itself, is smaller than in a Daniell of the same size, being about $\frac{1}{5}$ Ohm for a pint cell; the Voltage is generally about 1·8 Volts. If we connect the terminals of a pint Grove cell by a short thick bit of wire the current is 1·8 Volt ÷ 0·2 Ohm = 9 Ampères; the Heat developed per second is (Ampères)^2 × Ohms $= 9^2 \times \frac{1}{5} = 16\cdot2$ Joules, or 162,000000 ergs. If we again use our 80-Ohm coil of wire, the total Resistance becomes 80·2 Ohms; the Voltage is 1·8 Volts, as before; the current-strength is Volts ÷ Ohms $= \frac{1\cdot8}{80\cdot2}$ = 0·0224 Ampères; the Heat developed within the Cell is (Ampères)^2 × Ohms $= (0\cdot0224)^2 \times 0\cdot2 = 0\cdot0001$ Joules per second; the Heat developed in the Wire is similarly $(0\cdot0224)^2 \times 80 =$ 0·4000 Joules per second; and the Difference of Potential

between the ends of the connecting wire is Ampères × Ohms = $(\frac{18}{802} \times 80) = 1 \cdot 7955$ Volts.

5. Supposing we have a Cell whose **internal resistance** and **voltage** we do not know; but we have a set of **coils** whose Resistances we do know. Take three of these, say 5 Ohms, 10 Ohms, and 20 Ohms. With the aid of these the problem is not at all beyond the reach of calculation, provided that we have some means of **measuring the strength** of the Current directly **in Ampères**, as by means of instruments known as Ampère-meters or **Ammeters**. Let the result of our measurements be, then, that with the 5-Ohm coil interposed between the terminals of the cell, the current is 0·24 Ampères: that with the 10-Ohm coil it is 0·133 Ampères; and that with the 20-Ohm coil it is 0·0706 Ampères. If we set this out in an algebraical form the problem becomes simple; let V stand for the Voltage of the cell in Volts; let ω stand for the internal Resistance of the cell in Ohms; then we have the three equations $\frac{V}{\omega + 5} = 0 \cdot 24$; $\frac{V}{\omega + 10} = 0 \cdot 133$; $\frac{V}{\omega + 20} = 0 \cdot 0706$; and from these equations the student's knowledge of algebra will readily enable him to find that $V = 1 \cdot 5$ Volts and $\omega = 1 \cdot 25$ Ohms.

6. Suppose we had a Daniell cell, 4 Ohms and 1 Volt as before; and we want to **reduce the current** to 2 milliampères, that is, to $\frac{2}{1000}$ Ampères: what amount of **resistance** must we **interpose** between the terminals? As before, Ampères = Volts ÷ Ohms; that is, 0·002 = 1 Volt ÷ 500 Ohms; so that the whole Resistance must become 500 Ohms, and the **resistance interposed** must therefore be 496 Ohms.

We may have, instead of a simple wire between the terminals of a cell or battery, a circuit in which the different successive parts present differing resistances, as for example, an alternation of thick and thin lengths of wire. Then the **heat** produced in the whole circuit is **distributed** among the different parts of the circuit, **to each according to its Resistance.**

If a wire were a Perfect Conductor, it would present **no resistance**, and there would be **no heat** developed in it; and the conducting wire would thus be unaffected by the passage of the current. The Heat developed in any given portion of a circuit is therefore a consequence of the imperfection of the conductor employed.

We have, in all the above, assumed the Current to do nothing but transform **all its Energy** into **Heat**. But the formulæ, Heat $= (\text{Amp.})^2 \times$ Ohms $=$ Amp. $\times$ Volts $= (\text{Volts})^2 \div$ Ohms, also refer, more broadly, to **Energy** in **any** of the forms which it may assume. If the current be made to drive an electromotor, the **electromotor** is **equivalent**, from the point of view of the battery and circuit in general, to a **wire** presenting a certain Resistance and a certain Difference of Potentials between its extremities; and the only difference in the situation is that the motor more or less completely transforms the Energy supplied to it into the energy of Work done by it, instead of transforming it all into Heat.

It may be proper in this place to explain what the measure of Current is for commercial purposes. It is not the Strength of Current, the Ampères; this alone would not tell us how much Energy the consumer had taken from the electric mains; and from the point of view of the electric lighting company it is a matter of indifference what may be the special forms of apparatus employed by the consumer. What interests them is how much **Energy** they have supplied him with, and this is what, by one means or another, they measure in the consumer's meter. The rate of consumption of Energy in the consumer's apparatus is equal, when measured in Joules-per-second, to the product of the Ampères into the Volts. Consequently, by one means or another, the meter must register both the **Ampères** and the **Volts** under which the Energy of the electric current is supplied. But the meter must do more than this; it must also register the **Time**. The product (Ampères $\times$ Volts $\times$ no. of Seconds) gives the number of Joules of Energy taken up from the circuit. The **commercial unit** of Electrical Energy is 1 Ampère $\times$ 1 Volt $\times$ 3,600000 seconds $=$ 3,600000 Joules $=$ 1000 Ampère-Volt-Hours. It does not matter how this product is made up, whether by Strength of Current, or high Voltage, or length of Time, or all or any of these; whenever this product has been made up, the commercial unit of Energy has been consumed; and if, as is said, "the unit of current" costs 5d., the sum due is then 5d.

The same thing is often expressed in another form, namely:—the unit is equal to 1000 Joules-per-second continued for an hour; but the phrase "**Joules-per-second**" is abbreviated into "**Watts**," a Watt being the unit of Activity on the so-called

"Practical Electromagnetic" system, in which the Coulomb, Ampère, Ohm, and Volt serve as units systematically related to one another; that is, the Watt is an activity of 10,000000 ergs per second. Then the commercial unit is equal to the result of an Activity of 1000 Watts, kept up for 1 hour: it is said to be equal to 1000 Watt-hours or to one **kilowatt-hour**. On the Continent of Europe the unit in use is not 1000 Watt-hours, but 100; the unit is therefore a "**hektowatt-hour**," not a kilowatt-hour.

(*b*) Production of Light by a Current

(1) **Gaps in a circuit.**—We have already alluded to the production of the now well-known electric **arc light**. In this, in air, the positive carbon wears away about twice as fast as the negative: so that contrivances have to be resorted to for **regulating the approach** of the carbons towards one another as they wear away. In some cases, as in lantern projection work, it is found expedient to regulate the position of the arc by hand: in street lighting the devices employed must be automatic. The **temperature** attained is about 3500° C., at which carbon volatilises: and powerful lamps differ from weaker ones in the area of carbon over which this temperature is attained. Area for area, the **brightness** of the luminous part of the carbon is the same both in weaker and in more powerful lamps.

(2) **High temperatures in bad conductors.**—The **temperature** assumed by any given portion of the circuit will depend upon the **amount of heat** liberated in it (measured in calories); and it will be greater the smaller the **mass** of the portion considered, and also the smaller its **specific heat**. A very thin badly-conducting wire or filament may collect within itself, on account of its relatively high Resistance, a very **large proportion** of the total Heat developed in the whole circuit; and then, on account of its small Mass, its temperature may become exceedingly high in a short

time. When it is hot it will lose heat by radiation and conduction or convection; but it will attain a temperature at which its losses are balanced by the continuous supply of Energy from the battery, in the form of Heat. The smaller its radiating surface, or the less air it has immediately around it, the less rapid will be its losses, and the higher will its temperature tend to become before equilibrium is reached. A sufficiently strong current, passing along a very thin and short piece of platinum wire, may thus bring that platinum wire to a red or a white heat, or may even fuse it. Then, of course, when the wire becomes exceedingly hot it emits light.

The earlier suggestions as to the manufacture of small electric lamps were that the current should be made to pass through a thin platinum wire or a coil of thin platinum wire. These forms of lamp were, however, soon displaced by electric incandescent lamps in which the filament of high resistance is made up of a carbonised organic fibre such as a bamboo fibre, or—nowadays—of prepared carbon paste. The Resistance of these filaments is very great, ranging, in an ordinary 16-candle lamp, from 16·2 to 181 Ohms.

Suppose the current is so regulated that its actual strength as it passes through the lamp is 1·85 Ampères, and that the lamp is one of 16·2 Ohms resistance; then the Difference of Potential between the extremities of the filament is Volts = Ampères × Ohms = 1·85 × 16·2 = 30 Volts. Similarly if the current be 0·58 Ampères and the resistance 181 Ohms, the voltage is 105 Volts. In the former of these cases, the Energy transformed by the lamp is Joules per second = Voltage × Current = 30 × 1·85 = 55·5 Joules per second; in the latter of these cases it is similarly 105 × 0·58 = 60·9 Joules per second. The average consumpt of Energy by a 16 candle-lamp may be taken at from 50 to 56 Joules per second. The lighting power falls off to 13 or 14 candles in 100 to 200 hours; so that the consumpt rises to an average of 3¾ Joules per second, per candle-power.

The whole of the Energy radiated from the lamp does not take the form of Heat, for some of it assumes the form of the energy of Light; but after all this is only a small percentage, some 5 or 6 per cent at most. Hence it must be borne in mind that an electric **incandescent lamp** is **not** by any means **heatless**; if immersed in a small quantity of water it may **boil** the **water**, through the absorption by the water of the Heat radiated from the filament; and if such a lamp be wrapped up in **gauze**, the gauze may first char, then smoulder, and ultimately **take fire**; and disastrous fires have actually arisen from this cause. Again, when such lamps have to be introduced into **cavities of the human body** for purposes of exploration, it must be remembered that quite as much Heat is produced as if the same filament (or one of the same resistance) had been used bare and applied as an electro-cautery. Mischief may be caused by needlessly keeping the lamp alight when introduced into position; for though the actual white-hot filament is not brought into contact with any one point of the tissues, the Heat is radiated from it and is absorbed by a certain area of the tissues surrounding the lamp; and any carelessly protracted exposure of the tissues to this influence may result in undue stimulation or irritation, or even in a burn.

Lamps of this kind are very useful for **microscopical** purposes: for they may be made very small and may be brought into the focus of the condensing lens or mirror, so as to afford a sufficiently powerful and concentrated source of bright light, in the best optical position.

(3) **Geissler-Tubes.**—If a glass tube containing air, or other gas, only in very small quantity, that is, at a pressure of only about $\frac{3}{1000}$ atmosphere, have platinum wires fused through the glass and entering its cavity at opposite extremities; then if these wires be connected with the terminals of a frictional electric machine or a battery of high potential-difference, so that the rarefied gas is, as it were, invited to act as a conductor of the current, a very feeble current will pass through the gas; and the gas will then glow with a phosphorescent light.

This light depends, in respect of its colour and the lines in its spectrum, upon the nature of the material of the gas. Many proposals have been made to utilise the light produced by such vacuum-tubes, or "Geissler's tubes," for illuminating the cavities of the human body; but nowadays they are very little used, for the light which they produce is but feeble, and they have practically been replaced by the more convenient small electric incandescent lamps which are now obtainable. Geissler-tubes are usually set in action by means of the current from an induction-coil, which will be described later.

In a Geissler-tube, the **negative** electrode is surrounded by a **dark region**: and as the **rarefaction** increases, this dark region **lengthens** until at length it fills the tube. But the dark region is the scene of a most vehement **transport of molecules**, repelled from the negative electrode (or "cathode"): and if the negative electrode be so shaped as to make the molecules, travelling always at right angles to its surface, converge upon a limited area of the glass walls of the tube, that limited area will brilliantly shine with a **phosphorescent** light. There has been discussion during recent years as to whether this is really due to molecules travelling in the tube, or whether it may not be due to Longitudinal Vibrations of the Ether. Professor Röntgen, in working at this subject, discovered that the light from the phosphorescent area of the glass contained some form of apparent radiation which possessed extraordinary properties. It traverses paper, wood, aluminium, but not most metals; it is not regularly reflected and refracted; objects are more or less opaque to it according to their physical **density**; it makes fluorescent substances **fluoresce**; and it affects a **photographic plate**. Hence if the hand be held between the phosphorescent vacuum-tube and a photographic plate, the rays traverse the flesh and cartilages pretty freely, while the bones are relatively opaque; and if a needle be embedded among the bones, it will be very opaque; so that a **shadow-photograph** of the skeleton of the hand may be made, and will show the position of any metallic foreign body.

What the nature of this radiation, if radiation it be, is not yet clear; some think it to be due to **longitudinal waves** of the Ether; some think it due to an actual **permeation** of the transparent body by molecules from the source of light: and others think it entirely a phenomenon of **stress** in the electric **field**. It is remarkable that similar results are produced, in less degree, by the light from most ordinary phosphorescent bodies, particularly from artificial blende (sulphide of zinc).

(c) Electrolysis

When we pass a current of electricity along a wire of **metal**, nothing particular seems to occur within the wire, in the way of any displacement of the particles of the metal itself. But if we pass a current through a quantity of **acidulated water**, by immersing in it two platinum plates or "electrodes," which are themselves connected with the terminals of a sufficient galvanic battery, then we find that at the electrode connected with the "positive"* or copper (or carbon or platinum) terminal of the battery, **oxygen gas** is **liberated** in bubbles. At the same time, on the other electrode, that connected with the "negative" or zinc terminal of the battery, **hydrogen gas** is liberated in the same way, but in volume equal to **twice** that of the oxygen simultaneously liberated at the positive electrode. The easiest and most obvious conclusion to arrive at, on considering this result, would be that the electric current has *decomposed* the water into its constituent elements, oxygen and hydrogen. This was for a long time believed, and it is still usual to speak of the decomposition of water by the current.

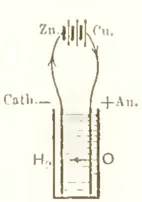

Fig. 251.

* This positive electrode is called the "anode"; the other, the negative, is called the "cathode."

But recent researches have made it clear that the explanation of the phenomenon has to be sought for in another direction.

The mechanism of the reaction seems to be somewhat the following. The sulphuric acid, H_2SO_4, when dissolved in water, breaks up spontaneously into hydrogen and the group SO_4. That liquid, which we call a Solution of sulphuric acid in water, consists of water as an inert medium, and of atoms and molecule-groups of hydrogen and SO_4 uniformly disseminated through it, together with some undecomposed molecules of sulphuric acid. The Hydrogen-atoms are positively charged; the SO_4-groups are negatively charged. How this comes to be, no one knows. Then the positively-charged hydrogen-molecules are attracted by the negative electrode, the cathode, the electrode connected with the zinc; and they are repelled by the opposite or positive electrode, or anode. Similarly the SO_4-groups are repelled by the cathode and attracted by the anode. The H atoms therefore drift through the medium towards the cathode, and the SO_4 towards the anode.

When the hydrogen-atoms reach the negative electrode or cathode they give up their positive charge, and they then coalesce to form ordinary hydrogen-molecules, which aggregate to form bubbles of hydrogen on the negative electrode. The hydrogen thus appears to travel with the current from the battery, from its copper terminal towards its zinc terminal. In this the water has taken no part; but if we follow up the history of the SO_4-groups, we find that these accumulate in the region of the positive electrode, and that there is a rearrangement of the atoms there, such that the reaction may be expressed by the chemical equation $SO_4 + H_2O = H_2SO_4 + O$. The result is the liberation of oxygen on the positive electrode or anode, and its aggregation in the same way to form bubbles. But this oxygen is the product of a secondary reaction, not of the direct decomposition of water by the current.

Again, in a solution of chloride of sodium, the chloride spontaneously splits up upon solution into atoms of chlorine and of sodium, which float equably disseminated in the water. When a current passes, the sodium atoms drift in one direction and the chlorine atoms in another, and accumulate in the region of the respective electrodes; the positive sodium atoms towards the negative, and the negative chlorine towards the positive electrode. Where the sodium atoms are in excess, they act upon the water surrounding them, and form soda hydrate, which remains in solution, and hydrogen, which escapes. Similarly, the chlorine atoms attack the platinum electrode, corrode it, and form **platinum chloride** ; and if we wish the chlorine to be evolved as such, we must use electrodes of carbon or some substance which is not attacked by chlorine. If the solution be one of **chloride of copper,** the **copper is not deposited** upon the negative electrode, for it is dissolved by the solution ; $Cu + CuCl_2 = Cu_2Cl_2$.

The phenomena of Electrolysis are thus phenomena of Drift or flow of previously-dissociated atoms, or groups of atoms, from the substances dissolved.

As the particles come up to the electrodes, they **discharge** into the general circuit the **quantities of electric charge** with which they are, somehow, endowed ; and thus the **current is kept up.**

It is to be observed that the Quantity of Charge with which a free atom is charged is always the same ; so that the discharge of a given Number of dissociated Atoms upon the electrodes is associated with the passage of a given Quantity of Electricity round the circuit, and no more. This is as much as to say that we may **measure the Strength of the Current** (that is, the Quantity of Electricity which flows per second), by the **quantity of the products** of apparent decomposition which appear at the electrodes during a second. The proportion in which the former stands to the latter is given us by **Faraday's Law.** To understand this law, we must first understand what a Gramme-Equivalent is.

Hydrogen in an acid can be replaced by a metal to form a salt. In hydrochloric acid, for example, hydrogen can be replaced by sodium to form chloride of sodium. In this instance, one gramme of hydrogen will be replaced by 23 grammes of sodium. The 23 grammes of sodium are thus equivalent to one gramme of hydrogen ; and this quantity of sodium, 23 grammes, equivalent to *one gramme* of Hydrogen, is called the **gramme-equivalent** of sodium. Similarly the gramme-equivalent of potassium is 39 grammes ; and the gramme-equivalent of iron is 28 grammes in the ferrous compounds, and $18\frac{2}{3}$ grammes in the ferric compounds. This last statement will be understood when we look at the formula of ferrous chloride, $FeCl_2$, and that of ferric chloride, Fe_2Cl_6 ; in the former, 56 grammes of iron have replaced 2 grammes of hydrogen in hydrochloric acid; in the latter 112 grammes of iron have replaced 6 of hydrogen. The Gramme-Equivalent of a **metal**, then, is the number of grammes which will **replace** one gramme of Hydrogen in chemical combinations. Again, the gramme-equivalent of a **halogen**, such as chlorine, or of a **salt-radicle**, such as SO_4, is the number of grammes of that halogen or salt-radicle which will **combine** with one gramme of hydrogen. Thus, the gramme-equivalent of chlorine in hydrochloric acid is 35·5 grammes, because in that acid 35·5 grammes of chlorine are united with each gramme of hydrogen.

Faraday's Law is, then, that when a current passes, whose strength is A Ampères, 0·000010,352 A Gramme-Equivalents of the salt-radicle or halogen are liberated at the positive electrode, per second; and a corresponding quantity of the metal in the salt acted upon is liberated at the negative electrode.

A current of one Ampère thus liberates upon the positive electrode 0·000010,352 gramme-equivalents of silver per second; that is, 0·001118 grammes of silver per second, or 4·025 grammes per hour. The Strength of a Current can, with the help of this datum, be measured by finding out how much metallic silver it will deposit from a solution of pure nitrate of silver in a given time.

The process of Electrolysis is utilised in **electroplating**. The object to be plated is made a negative electrode, or cathode, in a solution of the metal; that is to say, it is connected with the zinc of a sufficient battery, or with the corresponding terminal of any other source of electric current. The **metal** to be deposited **travels with the current** towards the negative electrode, that is, towards the object to be coated.

The solution tends to become weaker as it is robbed of its metal, atom by atom; but there is a contrary tendency acting at the same time, namely, the **corrosion** and solution of the **positive electrode** by the halogen or salt-radicle liberated there. For example, if a current be passed through a solution of sulphate of copper between copper electrodes, there will be a deposition of copper from the solution upon the *negative* copper electrode or cathode, and that electrode will be thickened; but the salt-radicle liberated in the neighbourhood of the positive copper electrode or anode will cause the solution of some of the copper from that electrode, with formation of sulphate of copper in the solution; this fresh supply of sulphate of copper is in its turn subject to electrolysis, and the copper, originally a part of the positive electrode, finds its way through the solution to the negative electrode, and contributes to thicken it. The whole of the positive electrode may thus be eaten away, and its substance transferred to the opposite electrode. In this way the solution, or "bath," employed in electroplating is kept saturated; the positive electrode is made of the metal with which the negative electrode is to be plated. If the **current** be **too strong**, so that the solution is robbed of its metal too rapidly, the atoms from the positive electrode **have not time** to come forward into the neighbourhood of the negative electrode, and the solution there becomes weak in metal, with consequences detrimental to the colour and consistence of the metal deposited.

There is thus always a well-marked tendency to corrosion of the positive electrode; and though this tendency may in some particular cases, such as that of plating above referred to, be utilised and turned to good account, the tendency to corrosion of the positive electrode is generally detrimental, and must be carefully kept in view.

Let us suppose that we are going to pass a current through part of the Human Body; and that we are using, as a **positive** electrode, a plate of **zinc**: and suppose that the positive plate is applied to the skin moistened with salt water in order to improve its conductivity, or to any naturally moist surface, such as a mucous membrane; then the salt water or the mucous secretion is electrolysed and chlorine is liberated at the positive electrode, that is, at the zinc plate; the zinc is attacked, with formation of **chloride of zinc**, which has a powerful **caustic** effect on the skin or upon the tissues. In particular cases, this caustic effect may be precisely what is desired, in which case a zinc electrode may be employed. Again, where it is intended to insert a needle into the tissues, the corrosion of the needle which is to be used as the **positive** electrode may be prevented or minimised by **gilding** it; then in the neighbourhood of this needle the nascent oxygen, chlorine, salt-radicles, etc., which are liberated on electrolysis, will produce their own effects on the surrounding structures, and will cause **coagulation of blood** and check bleeding or condense the tissues. If such a needle be inserted in an **aneurism** or dilatation of a large blood-vessel, and if a current be passed so that it enters by the needle and finds its way out by a metallic negative electrode placed on some other part of the body,—that is, if the gilt needle be made the **positive** electrode,—the result is that the local liberation of oxygen, chlorine, etc., within the aneurism causes **coagulation** of the blood within the sac, beginning round the needle, and thus the sac may be blocked up and the danger of its bursting averted. If, on the other hand, the current be passed the wrong way, so that the needle inserted in the sac becomes the negative instead of the positive electrode, the consequence of the electrolytic action is that there is an evolution of bubbles of hydrogen round the needle, and bubbles of gas are thus introduced directly into the blood-circulation, a result which may possibly have fatal consequences.

In the electrolysis of **tumours**, the **negative** needle is inserted into the tumour. Then the material round the needle becomes alkaline, and frothy with liberated hydrogen; and it is rapidly disintegrated.

Electrolysis furnishes us with a ready means of ascertaining **which** is the **positive** and which the **negative** terminal or pole of a battery. Take a bit of blotting paper or filter paper, moisten it with a solution of iodide of potassium, and touch it with the wires or needles from the two terminals. At one of the two wires the paper will remain white; at the other it will darken, on account of the liberation of iodine. The wire at which the **iodine** is liberated is the one connected with the **positive** terminal of the battery; it is the Anode, or the electrode connected with the **copper** or platinum or carbon of the battery, if the battery be one made up of galvanic cells.

It will be noticed that the **corrosion** of metal which is caused by Electrolysis, occurs where the **current leaves** the metal; thus where electric lighting or electric tramway currents escape and travel partly through the earth, taking advantage of the presence of gas pipes or water pipes to find an easy return path, these gas pipes or water pipes are corroded at every point where the current leaves them to enter moist earth, but are not affected where the current leaves the earth to enter the metal. In such cases **damp earth** acts as an **electrolyte**; that is to say, it acts as if it were a liquid solution of the salts contained within it; the salts are dissolved by the moisture present; the atoms travel as they do in a liquid; and thus we may find, in the neighbourhood of the wire or pipe towards which the current flows, aggregations of metallic sodium or potassium derived from the soluble salts of the soil, or more generally, accumulations of alkaline oxides or carbonates; while in the regions surrounding those points of the wire or pipe from which current enters the soil, we find that the soil is acid, and metal, of which the wire or pipe has been robbed, is found, generally in the form of oxide, to be slowly making its way through the soil towards some point where the current enters the wire or pipe.

Density of a Current.—In Electrolysis in particular, but also in considering the local development of Heat in a conductor, it is of importance to keep in view the so-called **Density** of the Current, that is, the **number of Ampères** running **across each sq. cm.** of a transverse section of the conductor. Where a conductor narrows down, the heating or electrolytic effects are concentrated: and in order to keep them from being excessive, a sufficient transverse-sectional area will have to be given to the conductor.

In medical applications of electricity, if a current of say 0·2 Ampère be passed through the body by means of **large electrodes** applied to the skin, there may be no inconvenience; but if the electrodes be **small**, there may be pain, blistering, and even sloughing produced.

(*d*) The Production of a Magnetic Field

The action of currents upon magnets, of currents upon other currents, and of currents upon soft iron, is such as to show that the **region of space surrounding a current** is a **Magnetic Field.**

It will probably be found easier to understand the bearings of this expression if we give at once a brief *résumé* of the main phenomena of **Magnetism** in this place, and then show what the relation is between these and the phenomena of a Current.

In a **Magnet**, for example in a mariner's-compass needle, there is one line called the **magnetic axis**, which always tends to lay itself in a particular direction. This direction lies, roughly speaking, North and South. A magnet also **attracts soft iron** towards the extremities of its magnetic axis.

One end of the Magnetic Axis has a special tendency to move towards the **north**, and the other has a similar and corresponding tendency to move towards the **south**. It is as if a pair of invisible hands laid hold of its ends, like the hands on the handles of a copying-press, and as if the one of these hands pulled the one end towards the north while the other pushed the opposite end of the magnetic axis towards the south.

The result is that the magnet tends to **rotate** into its north and south position, but there is **no perceptible tendency** to make it change its position by any movement of **Translation** : the action is confined to a rotatory movement. The Force upon the one end of the magnetic axis is equal to the opposed Force acting upon the opposite extremity, and the two **equal and opposed** Forces, acting at the two extremities of the magnetic axis, constitute a **couple**.

In ordinarily accessible places, therefore, there are Forces tending to work a compass-needle round into a **definite direction** : these forces are called **magnetic forces** ; any region of space in which these Forces occur is called a **Magnetic Field** : and the direction in which the rotating couple acts, the direction of the pull-and-push, or the direction in which the compass-needle comes to lie in equilibrium, is called the direction or the **Line of Magnetic Force** at the place where the needle is situated. Through every point in a magnetic field a line may be drawn, which line represents the local Line of Force : and the local magnetic forces tend to make the **magnetic axis** of any magnet **coincide** with the local Line of Force, so far as feasible.

The magnetic field whose forces work the ordinary **compass-needle** is the **Terrestrial Magnetic Field**.

It is curious that the strongest attainable magnetic field seems to produce no effect whatever on the **brain**.

The end of the Magnetic Axis which is impelled towards the north is called the **north-seeking** or, simply, the **north pole** of the magnet ; the other end is the south-seeking or **south pole**.

If we cut a magnet into little pieces, **each** of the **portions** is a **little magnet**. This can be carried on indefinitely, and it is believed that the Magnetism of a bar of magnetised steel is a property of its constituent **molecules**. It is also believed that the magnetism of a bar of steel depends upon its Molecules (which are in truth **already magnetic**) being **turned round** within the solid metal so that their similar poles are turned the same way, and their **joint effect** then becomes perceptible.

This may be illustrated by an experiment in which a glass tube filled with steel filings is laid within a coil of wire through which an electric current is passed: the tube is shaken so as to give the filings some freedom of movement. They then lay themselves lengthwise in the tube; and each filing becomes a little magnet. If now the tube be carefully withdrawn, so as not to disturb the filings, the tube of steel filings is found to act in all respects as a magnet. But if it be well shaken, so as to knock the filings out of their position of parallelism to one another, and to make them assume mutual relative positions which are promiscuously discrepant, the magnetic properties of the mass disappear, although if any particular filing be taken out and examined, it will be found still to be a minute steel magnet. The filings in this experiment each correspond to a molecule of the mass of steel in the theory just stated.

There are two ways of describing the action of a Magnet; by its **Poles**, and by the **Magnetic Circuit.** The former, by its Poles, is the more usual method.

A Magnet is said then to have two **Poles**, one at each end of its **magnetic axis**; and the Magnetic Forces in the Field, acting upon the magnet, act upon its Poles, which are as it were laid hold of and the whole magnet rotated into position. Conversely, the Forces exerted *by* the magnet are said to be exerted **by its poles**; and the phenomena are explained by means of a form of speech in which certain **imaginary** attracting or repelling **magnetic matter** is supposed to be situated at these Poles. And further, these Poles are, in the elementary theory of magnetism, mere **points**, so that the leading problems of Magnetism are reduced to the very simple form of problems of attraction to a point at one end and repulsion from a point at the other end of the Magnetic Axis.

This only approximately corresponds to the facts. If it were an adequate representation of the facts we would be able to map out the region surrounding a magnet by means of **Lines of Force**, all proceeding from one point and converging upon another, after the fashion of Fig. 252. But if we want to find out how the Lines of Force are disposed in the neighbourhood of an actual magnetic bar, we must use a quantity of **soft iron filings**, lay them on a card lying upon the magnet, and shake them a little, so that they may leap into positions spontaneously assumed by them; then we find that each little filing lays itself in its own direction along the local Line of Force, and that the congeries of filings assumes a form diagrammatically shown in Fig. 253. That is to say, the Lines of Force do not all start from a common point. There is therefore no such thing as a true magnetic Pole: there is, however, a **polar region** towards the end of each magnet, towards and from which the lines of force converge and diverge.

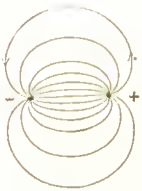

Fig. 252.

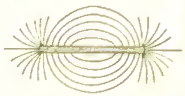
Fig. 253.

There may, however, be particular constructions in which the actual state of affairs may **approximate** more or less nearly to that of a true pair of Poles; for example, in a very **long**, very **thin** and **uniformly magnetised** wire: and it is on the whole convenient, for simplicity of treatment of the subject, to begin by assuming that the magnets of which we speak are magnets of this somewhat ideal kind. A pretty close approximation to fact is in many cases obtained by assuming that a long thin bar has true poles which are situated, not at its ends, but at some small distance from each extremity of the magnetic axis.

By a pure convention, which happens to harmonise with the conventional use of the terms Positive and Negative in Electricity, the **North-seeking** Pole of a magnet is said to be its **positive pole**; the South-seeking Pole its Negative pole. Then in different magnets, poles which are **both positive** or **both negative repel** one another: poles which are **dissimilar attract** one another.

Magnets vary in **strength**: some are stronger, some weaker than others; and the Strength of a magnet is measured by the mechanical resistance which we must offer in order to **prevent** it from swinging round, when suspended, into the north-and-south position which it tends to assume. Then a magnet is supposed to have, in proportion to its strength, a certain **quantity** of the imaginary Magnetic Matter at each of its poles: that is, a positive quantity at its north-seeking pole, and an equal negative quantity at its south-seeking pole. And next, magnets act upon one another, if their poles be approximately mere Points, in a way which may be expressed by saying that **each pole** acts upon **every other** with a **Force proportional** to the **Strength** of each Pole and *inversely* proportional to the *square* of the **Distance** between them: a law which is of the same form as the Law of Gravitation. Between similar poles this force is one of Repulsion; between dissimilar poles one of Attraction.

In order to have a standard for measurement and comparison we say that a pole is (in C.G.S. measure) a Pole of **Unit Strength** when it repels an **equal** pole at a Distance (through air) of **one centimetre** with a Force of **one dyne.**

Terrestrial Magnetism.—The neighbourhood of the Earth is a great Magnetic Field, **nearly uniform** within small distances. In this field the Lines of Force have, at each point of the earth's surface, determinate directions. They slant in the **northern** hemisphere **downwards** and roughly speaking northwards; in the southern hemisphere upwards and northwards. But they are far from being geographically parallel to one another, so that for example at Greenwich they point downwards, making an angle (in 1895) of 67° 15′ with a horizontal line and an angle of 17° to the west of north: whereas at Valentia on the west coast of Ireland they make an angle of 68° 45′ downwards and 22° 11′ 54″ to the west of north. The local angle which a compass-needle makes to the west or east of true or geographical North is called the **Declination**: sailors call it the Variation. The downward or upward angle made with a horizontal line is called the **Inclination** or **Dip.** An ordinary mariner's compass is weighted so as to prevent the needle from dipping downwards; but there is an instrument called a **dipping compass** in which the object is to allow the needle to dip, so that we may ascertain what the inclination is. In this instrument the needle is poised on a horizontal axle; and it is turned round on a vertical axis until the dip of the needle attains a maximum: the magnetic axis of the needle then lies along the local Lines of Force, and this contrivance then shows the magnetic north and south as well as the amount of the Dip.

At any place a vertical plane parallel to the Lines of Force is called the "**Magnetic Meridian**" at that place. In physical maps of the earth we find irregular lines marked **Magnetic Parallels** and **Magnetic Equator**. The Magnetic Equator is a line at every point of which the **dip** is equal to **zero**, so that the needle lies horizontally after magnetisation if it lay horizontally before being magnetised; and the Magnetic Parallels are lines joining localities at which the **Dip is equal**. These lines are far from coinciding with the geographical Equator and parallels of latitude. As we near the Arctic or Antarctic Poles, we find the magnetic parallels become very irregular curves, and the needle points to their Centre of Curvature. This gives the impression that these centres of curvature are magnetic poles of the earth: but a true Magnetic Pole of the Earth is a place where the **needle** stands **vertical**, the dip being 90° there: and there are only two such points, one in the Arctic, one in the Antarctic region.

All the magnetic data or "**magnetic elements**" of any one place undergo continual changes or **variations**: the magnetic equator and parallels are always shifting, the magnetic meridians twisting, and the strength of the terrestrial magnetic field varying. Some of these variations are rapid, some are very slow and take ages to accomplish their course: some depend on the relative position of the sun and moon: some upon the physical condition of the sun.

In a good many forms of apparatus it is, as in galvanometers, of advantage to mask the Earth's Magnetic Field, or more or less completely **neutralise** its effect upon a magnetic needle. This will enable a given magnetic needle to be deflected from the magnetic meridian by a less powerful force. This weakening of the field surrounding the galvanometer-needle may be accomplished by bringing **another magnet**, with its **north** pole lying **north**, to an adjusted distance above the galvanometer needle, so as almost to neutralise the earth's directive force; or by coupling together on the same suspending thread two almost equal magnetised needles with their **poles opposed**. If the two needles were exactly equal and had their magnetic axes parallel, the system would be practically unaffected by the earth's directive action. Such an arrangement is said to be "**astatic.**"

The reason why a magnet with its north-seeking or positive pole lying North tends to neutralise the Earth's directive forces is this, that the Earth itself is really a magnet with its positive pole lying to the South; for its positive pole is its Austral or Antarctic, not its Antarctic Pole. Then the lines of force due to the Earth, and those due to the neutralising magnet, are opposed in direction.

Magnetic Circuit.—Refer again to Fig. 252. We see there that the Lines of Force in the immediate neighbourhood of the magnet appear to **emerge** from one end and to **return** to the other end of the Axis. But this would be an incomplete view of their relations. Let us assume an ideal magnet of some appreciable **thickness**, a magnetised iron bar, **perfectly uniformly magnetised** throughout: then the lines of force would all emerge at one end and return, by a more or less ample sweep, to the other end of the bar; but they would also be **continued through the bar**, so that each Line of Force forms a complete **closed circuit**, partly in iron, partly in air. Then the Poles of such a magnet would be the **flat ends**, at which the Lines of Force pass from air into iron or from iron into air; and the Lines of Force would have **directions** such as those shown in the diagram, passing from the positive to the negative pole in air and through from the negative to the positive in the iron itself.

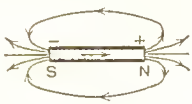

Fig. 254.

If a little magnetised steel filing were laid in the neighbourhood of this magnet, it would act as a compass-needle does in the neighbourhood of the earth: it would come to lie along the Line of Force passing through its Centre of Mass. The positive pole of the filing would come to lie as far away, along the line of force, from the positive pole of the magnet as it can; and the negative as near to the positive pole as it can.

There is **no limit** to the **distance** at which a **magnet acts**; there is no point, however distant, at which Lines of Force from any given magnet cease to appear; but of course at distant points the field of force due to any particular magnet may be so exceedingly **feeble** that we have no means of detecting it. At reasonably close quarters, however, we may **detect** the existence of the **Magnetic Field** of one magnet by the circumstance that **another magnet** tends to be **rotated** into the direction of the Lines of Force of the first; one of its poles is pulled, the other pushed along these lines; and all this corresponds to **stresses** and strains **in the Ether.** The extent to which such a detector-magnet will be pulled or tend to be pulled out of its normal north-and-south position will depend upon two things; (1) upon the local "**strength**" or "intensity" of the **magnetic field** in which it is swung; and (2) upon the **strength** of the detector-magnet's own **poles**, together with the amount of leverage provided by its greater or smaller **length.** These two latter data may often be taken jointly; we may not know the actual Distance between the "poles" of the detector-magnet or the Strength of its poles, and yet we may know the *product* of these. This product is called the **magnetic moment** of a magnet; and for a great many purposes it is all that we need know concerning a magnet.

Then if we assume that the magnet is **uniformly magnetised** throughout, so that any little bit of it would be precisely like any other little bit, of the same size and shape and cut out of the magnet in the same direction, we may divide the Magnetic Moment of the magnet by its Volume and arrive at the "Magnetic Moment per unit of Volume," say per cub. cm.; then we call this quotient the "**intensity of magnetisation**" of the magnet. This ought to be uniform throughout a bar magnet: if it were, all the **north and south poles** of the respective portions of the magnet (which would become manifest if the magnet were cut across into pieces) will completely **mask** each other; but generally there is a failure in this respect; and this may go so far that there is actually a reversal at some spot, where south poles may face south poles or north poles north, and thus we may have "**secondary poles.**" In such a case the Lines of Force will be complicated after the fashion indicated in Fig. 255.

Fig. 255.

The next case of importance is that of a **very thin slice** cut **transversely** out of a **uniformly magnetised** thick iron bar. Let AB be a section of such a slice; then the Lines of Force are as shown in Fig. 256. It will be understood that a larger diagram would better show that every Line of Force takes a sweep into space

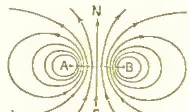

Fig. 256.

and returns, forming a **closed circuit** through the slice of iron. Those from near the edges turn sharply round and return: those from nearer the middle may take very wide sweeps before they return. The face of the disc lying towards N is its **positive face**, and that lying towards S its negative.

Now we come upon an extremely important proposition, which is the connecting link between Electricity and Magnetism; that if we take a **loop of wire**, of the same **size and contour** as the Magnet-slice or disc of Fig. 256, and pass round that loop an **electric current**, there will be, **around that loop**, a **Magnetic Field** of **exactly the same form** as that shown in Fig. 256; and if we use a **current** of **suitable strength**, the Magnetic Field due to the Current will be **identical** in all respects with that surrounding the Magnet-slice or disc already referred to. And further, if instead of a single loop of wire we use a **spiral** of wire, whose outline shall correspond with the outline of our thick bar magnet, Fig. 254, the magnetic field due to the current will be precisely the same as the magnetic field of Fig. 254. With this **difference**, however, in both cases: that whereas with an iron or steel magnet we cannot get inside the metal, the loop or the spiral is open, and we can ascertain that there is a Magnetic Field in the interior; so that the Lines of Force do truly form Closed Circuits, as is alleged.

An **electric circuit** may thus be said to be a **particular form of magnet**: if it is a mere **loop**, it is like a magnetised **disc**, with a **positive** and a **negative face**; if it is a **spiral**, it is like a magnetised **bar**, with a **positive** and a **negative end.** If the current be stronger, the circuit corresponds to a stronger magnet; if weaker, to a weaker.

Attention to this has enabled a Magnetic System of Electrical Units to be devised, which, with some modifications, has led to the adoption of the Ohm, the Volt, the Ampère, etc., with which we are now acquainted.

Since a simple circuit bearing a current corresponds, as a whole, to the magnetised disc of Fig. 256, it follows that the Circuit as a whole has itself a positive or **north-seeking** face and a negative or south-seeking face, and that it tends to lie, if it can turn into that position, with its faces magnetic north and south. Which, then, is the Positive Face of the circuit? The answer is that an observer **looking at** the **positive face** of the circuit, if he could see the **current**, would see it go round the circuit in a direction **opposed** to that of the **hands of a watch.**

Then, the student will see that if Fig. 256 be taken to represent a circuit-current, with its accompanying lines of force, all looked at edgewise, the current must be going away from him where it crosses the plane of the paper at B, and approaching him at A. He will also see that a **magnet-needle**, which always tends to lie along a Line of Force in the magnetic field, will turn so as to lie at **right angles to the wire**, with its north pole driven in the direction of the arrows in the figure.

The action of Currents upon Magnets.—If we now confine our attention to any particular **small part of the circuit**, namely, to so many inches of wire; and if we bring that part of the circuit near a **magnetic needle**; that needle will tend to lie **across the wire** if there be a Current in the wire, and its north pole will be deflected in a direction which indicates in which **direction** the **current** is flowing **in the wire.** This direction may be remembered by the following rule, which appears to the author to be the simplest means of calling to mind the relation in question which he can lay before the reader. Hold a **penholder** in the hand, the right hand, in the usual way; the pen points in a certain direction, the direction of the natural flow of ink in the pen, towards the point of the pen; suppose that the penholder represents the **wire**, and the direction of the **flow of ink** in the pen, **towards the point**, the direction of the **flow of current** along the wire. Then instead of allowing the **thumb** to lie stretched along the penholder, lay it **across** it. The thumb then represents the **magnet** as displaced by the influence of the current: the **thumb-nail** represents its "**marked**" or "north-seeking" end. When this is understood, the penholder may be laid aside and dispensed with; and the relation may be brought to mind by simply laying the **thumb across the forefinger** of the **right** hand; then the forefinger may represent the Current, flowing in the direction in which the forefinger points, and the thumb the Magnet, with its north-seeking end represented by the thumb-nail. With the thumb still lying across the forefinger, these relations may, if convenient, be exactly reversed, so that the thumb represents the Current, flowing towards the thumb-tip, and the forefinger the Magnet, with the finger-nail marking off its north-seeking end. The figure will also explain this relation (Fig. 257).

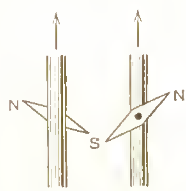

Fig. 257.

In the **Simple Galvanometer**, or Galvanoscope, used as a lecture-table apparatus for demonstration purposes, the wires are arranged as shown in Fig. 258. The magnetic needle NS is poised or suspended in any convenient way. The wire from a battery is brought first over the needle, then under it, and back to the battery. A key serves to close or complete the circuit when desired. The wires, which lie in the same vertical plane, are brought round until they come to lie in the **magnetic meridian**, that is, in the same plane with the magnetic needle in the position which of its own accord it tends to assume, lying magnetic north and south. When the wires and the needle are in the same plane, not before, the current is turned on by completing the circuit. If the relations be those shown in the figure, the north-seeking or N-marked end of the magnet is, by the part of the current lying above the needle, turned into a position above the plane of the paper in the diagram; and by the part of the current lying below it, it is farther driven in the same direction.

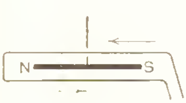

Fig. 258.

The deflection induced may thus be made to serve for the **detection** of a Current passing through the wire: and the effect will be multiplied if instead of one loop of wire as in the figure, we fit up a **coil** of insulated wire, so that the current may circulate several times round the needle. **Each turn** then produces its own effect; and feebler currents may be detected with a coil than with a simple loop of one turn.

But the deflection may also be made to show the **strength** of the current. The greater the deflection, the greater the strength of the current: a feeble current will cause a comparatively small deflection as against the pull exerted by the Terrestrial Magnetic Field; a stronger one a greater.

Suppose two persons take hold at the same time of the two handles of a copying-press, and try to turn the handles in opposite directions; the position assumed by the handles of the copying-press will be something intermediate between the positions into which either person could have brought the handles if unresisted. The two Couples are then in Equilibrium. When the action is of this kind, we have two cases of practical value: (*a*) the Forces are at **right angles** to the **natural position** of the needle, in which case the current is proportional to the *tangent* of the angle through which the needle becomes deflected in the passage of the current: thus, if BAC be the angle of deflection from the magnetic meridian AB, then if BC be drawn at right angles to AB, the current producing the deflection is proportional to the ratio BC/AB: and (*b*) the case in which the Forces acting are always at **right angles** to the **actual position** of the needle, in which case the current-strength is proportional to the *sine* of the angle of deflection, that is to the ratio BC/AC. These two cases are utilised in the Tangent Galvanometer and the Sine Galvanometer respectively.

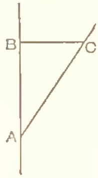

Fig. 259.

In the **Tangent Galvanometer**, there is a coil of wire wrapped round the circumference of a circle. This coil is mounted vertically, but in such a way that it can, as a whole, be turned round a vertical axis; the current to be tested can be passed round this coil, there being binding screws provided for this purpose. In the centre of the vertical circle there is poised a very short magnetic needle, which naturally tends to point north and south. The coil is brought round until its plane coincides with the north-and-south direction assumed by the needle; and *then* the current is passed through. The needle now deflects. The amount of its deflection is observed, and by the aid of tables which inform us as to the values of the tangents of different angles, we may calculate the proportionate values of the current-strengths which give rise to the different deflections observed. The instrument should be **standardised**: that is, it should be ascertained what deflection is produced when the current actually passing is **one Ampère**: then the deflections produced by currents of other strengths are proportional to the tangents of the respective angles of deflection: and an instrument so standardised may serve as an **Ampère-meter**. The instrument may be so constructed as to enable us to dispense with reference to mathematical tables. If in Fig. 260 the needle NS, poised at O, be provided with a long pointer, and if the deflections be read off on a **straight scale**, the readings on this scale represent the tangents directly, and the strengths of the current are proportional to those readings: so that we need not trouble ourselves about the number of degrees in the angle of deflection.

Fig. 260.

In the **Sine Galvanometer**, we again have a vertical coil of wire free to rotate round a vertical axis; the needle is poised as before, but may be longer than in the Tangent Galvanometer. The difference between the Sine and the Tangent Galvanometer is that in the former the current passes continuously; the needle deflects: the coil is rotated so as to try to make it lie **parallel** to the **needle**; this somewhat alters the position of the needle itself: but the attempt is pursued until it is successful, and the needle and the coil lie in the same plane. Then the strengths of the currents are proportional to the sines of the angles of deflection produced; and if the instrument be properly standardised, the strength of the current passing can be ascertained in Ampères.

Both in the Tangent and in the Sine Galvanometer it is of great importance that the **coil** should not itself offer such a **resistance** as materially to modify the strength of the current. Hence these instruments are often made with a single thick copper strip instead of a coil: but the advantage of a coil is then lost, namely, that each turn of the coil acts so as to increase the effect, for each turn of the coil is equivalent to an increase in the strength of the current passing round the needle.

To give an idea of the working of a Tangent Galvanometer, it may be stated that at Greenwich in the year 1896, with a tangent galvanometer of one turn, in which the vertical circle has a radius of 10 cm., the deflection produced by a current of one Ampère is 18° 53½′; and that produced by a current of 100 Ampères would be 88° 19½′, for the tangent of the latter angle is equal to 100 times the tangent of the former.

Again, the tendency of the needle to be deflected may be restrained by a **spring**: and the amount of Tension or of Torsion which must be applied to the spring in order to prevent the needle from deflecting at all may be measured.

In a **Differential Galvanometer** there are two coils, wound together round the same needle. Currents are sent round these coils in opposite directions; and if these be **equal** there is **no effect** on the needle; if one be stronger than the other, there is a deflection, due to the **difference** between the two currents.

The ordinary method of **Telegraphic Signalling** is by the use of a Key, by which the circuit can be closed for longer or shorter periods. The **longer** or **shorter** currents cause a **galvanometer needle** to twitch visibly in accordance with the signals transmitted. Sometimes the signals are not short and long, but positive and negative, the key being devised so as to commute the direction of the current sent round the circuit, according to the way in which it is handled; in that case the signals will be **right** and **left** deflections of a galvanometer needle; or right and left deflections of a **spot of light** on a screen, produced by a small mirror attached to the small deflecting needle; or they may be higher and lower notes on a **pair of bells** rung by one of two electromagnets in fixed magnetic fields.

The action of Currents upon Currents.—To understand this we may refer again to the comparison of an electric circuit to a magnetised disc. Two such Magnetised Discs, with their similar faces looking the same way, tend to slip together so as to have the same centre: and so will two circular Circuits, bearing Currents which run **parallel** to one another (Fig. 261). If their similar faces look opposite ways, the two magnetised discs slip off one another, and rotate, so as to make their similar faces look the same way: and so will two circular currents

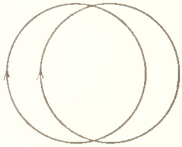

Fig. 261.

whose directions are **opposite**. The position of **stable equilibrium** of two such current-bearing circuits is attained when their respective currents run **parallel** to one another, and as **close together** as possible.

If the two coils be one larger and the other smaller, and both mounted on the same vertical axis, so that the smaller one may rotate within the larger one, they will, when currents are passed through both, tend to come into the **same plane** with their **currents parallel** to one another; and then in order to turn the inner one out of that position we must employ Force, that is to say a rotating Couple or Torque.

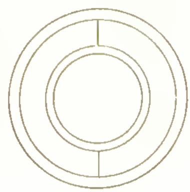

Fig. 262.

This rotating couple is such, at any given angle of deflection, that it is proportional to the *sine* of the **angle of deflection** (that is, in Fig. 263, if BAC be the angle through which the inner coil is twisted from a position in the line AC, it is proportional to BC/AB), and also to the **product** of the **current-strengths** in the two coils: it also depends on the **number of turns** in each coil, and on the **relative sizes** of the two coils. But now let the instrument be so constructed that the **same current** passes through **both coils**; then instead of the product of the two current-strengths we have the rotating couple proportional to the *square* of the one current-strength, that, namely, which we may wish to measure. Therefore if we find how much Torsion we must apply to a spring in order to force the two coils to stand at right angles to one another (instead of allowing them to stand in the same plane), we have an easy means of ascertaining directly, when once we know how much torsion is required for one Ampère, what is the *square* of the current-strength (in Ampères): and from this we may readily calculate what the current-strength itself is. Or else the instrument-maker, instead of graduating the torsion-dial in degrees, may graduate it himself in such a way as to enable the number of Ampères to be read off directly. This double-coil principle is the principle of construction of **Siemens's Electrodynamometer.**

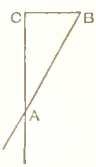

Fig. 263.

Let a current be passed through an outer bobbin of insulated wire; if an inner bobbin be free to move up and down along the axis of the former, and if a current be passed through the inner bobbin, parallel to that in the outer, the inner bobbin is sucked in to the outer one, for all the turns of the two coils tend to lie as close together as possible. If the same current pass through both bobbins successively, the Force pulling the inner bobbin into the outer again varies as the *square* of the current-strength. We may prevent the inner bobbin being sucked in, by trying to withdraw it by means of a spring, until we get it into a standard position: and when it is in that standard position the spring will be stretched to a certain extent, on the principle of a Spring-Balance. Then we know, by reading the scale, how much Force is being exerted, and, as before, the instrument may be standardised.

Wherever the indication of a current-measuring instrument is proportional to the square of the current passing, it will always be the same, whatever be the direction of the current.

Of course in the mechanical construction of instruments of this class, the actual movements or the spring-torsions or -tensions to be compared may be rendered manifest and measurable by making them move pointers on a dial, by means of appropriate gearing.

The subject of the action of Currents upon other Currents was not approached by the earlier experimenters from the magnetic point of view, or from that of the behaviour of complete Circuits. They looked at the more obvious action of a simple wire, bearing a current, upon another wire bearing a current; and they arrived at the following propositions as the result of experience.

Two currents running parallel and in the same direction attract one another; that is to say, the current-bearing wires tend to approach one another.

Two currents running parallel and in opposite directions repel one another; the wires tend to move apart.

When the currents are not strictly parallel, but both have the same general direction, they attract one another and tend to assume parallelism. When they have directions which are on the whole opposed to one another, they tend to move apart and also to rotate into a position in which the currents run parallel and in the same direction, in which position they attract one another.

Two currents running in the same direction, **end-on** to one another, **repel** one another.

Suppose a current is passed through a solenoid or spiral coil of wire: in the different turns the currents are parallel to one another and in the same direction; the different turns of the coil attract one another, and the coil tends to **shorten**.

Action of a Current on Soft Iron.—In order to explain this, we may return to our **magnetic circuit**, the lines of which thread the axis of a current-bearing **spiral** or "solenoid."

If we choose, we may say that the air within such a spiral is itself a **magnet made of air.** The essence of a magnet is not that it be made of iron or of any other substance, but that Lines of Force, or, as we shall now call them, **lines of induction,** run directly through it. Therefore, wherever there are lines of induction passing through air, the air itself becomes magnetised: strongly where the lines are crowded together; feebly where they are few or have diverged much from one another. But be it more or less at any given point, this magnetisation of the air affects the whole Magnetic Field; and it therefore generally involves the **whole Ether of space** in those strains and stresses which we represent to ourselves by means of Lines of Force or of Induction.

The lines of induction must form **closed circuits**; and in ordinary magnets the **magnet** itself only furnishes a **part of the path** traversed by the lines of induction. It is possible however to arrange matters so, in some cases, that these Lines may travel **wholly in metal**: in such a case the lines do not escape to the outer air. A good dynamo machine should present a good metallic circuit for these lines: and one's watch-spring ought not to be at all affected by being brought into the neighbourhood of an ideally good dynamo, which would confine its magnetic field wholly within its own metal.

Confining ourselves in the meantime to the region within the spiral, let us **replace the air** in that region by an equal bulk of **soft iron,** by slipping a soft iron bar into the spiral. The magnetic field surrounding the spiral is then say 300 to 400 times as strong as before; and the soft iron acts like a magnet 300 to 400 times as strong as the original air-magnet had been: 300 to 400 times as many lines traverse its substance. Why this should be so is a mystery.

This number, 300 to 400 in this case, is called the **Magnetic Permeability** of the substance acted upon. In iron, this permeability depends upon the quality of the iron; and there are some alloys of iron known which make magnets not a whit stronger, as magnets, than our original air-magnet.

Suppose that instead of leaving our **soft-iron core** wholly in the spiral or "solenoid" coil, we **withdrew** it gradually, in the direction of its length. Fewer and fewer of the turns of the solenoid would surround the soft iron: the effect of the soft iron in increasing the number of lines which thread the solenoid would become less and less. When the core has come completely out of the coil, the effect of the soft iron is not *nil*, for it still receives some of the lines, those in a weaker part of the field, and it increases the total number of lines which thread the coil; but the extent to which it does this diminishes as its distance increases: and thus the **strength** of the Magnetic **field within the coil** diminishes as the core is withdrawn, and may be **regulated** to any nicety between its full value when the core is wholly in, and its mere air-value when the core is wholly removed. We may see this in **Medical Induction Coils**: there are two coils, of which one slips over the other; the inner one carries an interrupted current: the field of force is occupied, within the coil, by a soft-iron core whose position is, in some models, capable of adjustment for the purpose of modifying the strength of the field in the way above explained.

If the iron be **very soft** it **loses** its magnetic properties the instant the Current **ceases**: but few specimens of iron are as soft as this. Steel does not strengthen the field to the same extent as soft iron does; it has not so great a Magnetic Permeability; but when the current ceases, the steel **retains** in large measure its magnetic properties and is a so-called **permanent magnet**, with its Magnetic Circuit and (if it have free ends) its Poles and its surrounding Magnetic Field. All steel magnets are now made in this way.

The lines of force which remain tend to **shorten** and shrink and disappear. This accounts for their form as shown in Fig. 253; and it accounts for a certain slow **spontaneous demagnetisation** of a magnetised steel bar. Hence steel magnets should always be kept in the manner shown in Fig. 264, with cross-bars of soft iron; but the whole should be arranged so as to provide a complete **magnetic circuit** for the lines, all (or as far as may be in view of the needful air-gaps) within the substance of the magnets themselves. If magnets be of a horse-shoe shape they should always have a soft-iron cross-bar or "Armature" on, for the same reason: the lines tend to pass through this instead of through the surrounding air. The **field** in the neighbourhood of a horse-shoe magnet is thus very much **weaker** when the armature is on than when it is off; it is weaker even when the armature is almost on, than when it is removed to a distance; and thus it is possible to **regulate**, not the Strength of a Magnet, which for a steel magnet remains practically the same, but the **strength of the field** between the poles of a horse-shoe magnet, by bringing a soft-iron armature to a greater or smaller distance from its poles. This is found utilised in the common **medical magneto-electric machine**, in which, as is said, "the strength of the magnet is regulated" by an **adjustable** piece of **soft iron** which, when it is brought near the magnet poles, **weakens the field** by drawing off, through its substance, some of the lines of that field.

Fig. 264.

A bar of **soft iron** acted upon in the way described, is an **Electromagnet**; and the power which very soft iron possesses of **instantaneously losing** its magnetic field when the current ceases, just as air will do, is of the greatest value; for it can be applied in the most varied forms of apparatus. Again, if we push up the **strength** of the exciting Current, increase the number of **turns** of the spiral round the iron, and use a **thick bar** of soft iron, we may make an immensely **stronger magnetic field** in its neighbourhood than we could by any combination of **permanent steel magnets** of the same size.

Electromagnets have been used, stronger than steel magnets of the same size could be, for drawing iron out of the eye, steel needles through the skin, etc.

Some Energy is lost in setting up the magnetic condition of electromagnets; and this is restored, as **Heat**, when the exciting current is arrested.

The exciting current can be readily made and broken by closing a key K, Fig. 265, and letting it go; when the current is made, the soft-iron bar becomes an Electromagnet, and it **attracts** a piece of **soft iron** poised in the neighbourhood of one of its extremities; when the current is broken by the release of the key, the electromagnet loses its magnetic properties, and the attracted piece of soft iron **returns** towards its original position; and the movements of this attracted piece or "armature" of soft iron may be utilised so as to work any form of mechanism which may accomplish the particular purpose in view.

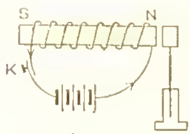

Fig. 265.

For example, in telegraphy, sometimes the current which the operator at the sending station sends on does not go all the way to the receiving station, which may be too distant to receive the signals with ease or certainty. In that case the currents sent may simply govern the movements of a small armature of soft iron at an intermediate station; and this armature may, by its movements, make and break the current for a circuit lying beyond it. By this device, known as a **Telegraphic Relay**, signals may be sent over very great distances.

Round a limited portion of the circuit, say a few inches of the wire, we have analogous results. We have seen that the **lines of force** close to the **wire** are small closed curves, **almost circular**; and a bar of soft iron, laid along any of these Lines of Force, will become, for the time being, an Electromagnet.

Let a wire be made to pass vertically through a hole in a piece of card, and let the card be held horizontally, with the wire at right angles to it; and let **soft-iron filings** be sprinkled on the card. The iron filings will of course lie on the card as they happen to fall, and their directions will be promiscuously discrepant. Now let a Current be passed along the wire, and let the card be slightly shaken so as to permit the filings to take up any position which they may then tend to assume. It will be found that they arrange themselves on the card in **closed lines**, almost in circles, round the wire. Each filing has, under the influence of the current, become a little magnet like a small compass-needle: and like a compass-needle it tends to turn round so as to lie across the current-bearing wire, and along the local Line of Force.

If in Fig. 257, p. 407, the needle there shown be one of soft iron, it will, if laid across the current in the manner shown, become an electromagnet: and its induced poles will be the same as those marked in that figure. The **finger-and-thumb rule** already given is therefore also applicable to the **position** of the **induced poles** in their relation to the inducing current.

Magnetic Induction.—Whether the Magnetic Field be due to a magnet or to an electric current, it is identical in its properties; and it is usually said that one of the properties of that Field is the power of producing **Magnetic Induction.** This is nothing more than that a bar of iron laid along the Lines of Induction in a magnetic field assumes magnetic properties, as we have just seen. If we lay a bar of soft iron end to end with a permanent magnet it becomes temporarily magnetised; if it be of steel it becomes permanently so. If we bring a bar of soft iron near one end of a magnet, it becomes magnetised, and its farther end is repelled while its nearer end is attracted; but the farther end, because it is farther off, is in proportion less repelled than the nearer end is attracted, and therefore on the whole the bar of **soft iron** is attracted by the magnet. A bar of **soft iron** is **always attracted** by a magnet, for it has of itself no magnetic properties and its nearer induced pole is always dissimilar to the nearer pole of the attracting magnet. A permanently **magnetised bar of steel** will, on the other hand, have its **one end attracted** and its **other end repelled.**

The Lines of Induction may be **continued** through several bars as if through one long one; and thus a magnet may support a chain of soft-iron nails, of which each becomes for the time being a magnet.

Fig. 266.

If the iron acted upon by induction be not perfectly "soft," it may not lose all its magnetic properties at once when the exciting magnet or current is withdrawn; but if it be shaken, hammered, or heated, it may lose them completely.

In the instance of soft iron, the induced magnetic positive pole is as **far away** from the inducing positive pole as it can go; and the bar ranges itself **lengthwise** along the Lines of Induction; but in most substances it is as **near** as it can come, and the induced positive pole lies between the inducing positive pole and the induced negative pole. Such substances are called **diamagnetic** substances: and these, instead of lying with their lengths along the Lines of Force, tend to lie with their **lengths across** these, so that they are magnetised transversely. Of these substances, bismuth is an example: but all diamagnetic substances are only very feebly affected by magnetic induction, and differ very little from mere air.

From what has been said as to the identity of action in the field of magnetic force surrounding a magnet and that surrounding a closed current, and from the obvious fact that Magnetism is a property of the smallest particle of a magnet, it has been inferred that in a magnetised body the **molecules** themselves have **electric currents** circulating round them. Of these any two contiguous ones neutralise one another's external effect (Fig. 267); but the outer parts of the currents in the outer molecules remain, and these, taken together, correspond to the current along the wire of a solenoid coil. As to the **directions** of these currents, it is inferred that if we look **endwise** at the **north-seeking pole** of a magnet, and could see the Molecular Currents to which the magnetism of the magnet is due, we would see them flow in a direction contrary to that of the hands of a watch, as in Fig. 267.

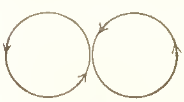

Fig. 267.

If we have **only air** in the **magnetic circuit**, the Strength of the magnetic **field** is *directly* proportional to the strength of the **current**: and this gives us a means of ascertaining the relative Strengths of two Currents passed through the same spiral of wire. If there be **iron** in the magnetic circuit, we do not get say ten times as strong a magnetic field by using ten times as strong a current; for the **permeability of iron falls off** in proportion, the stronger the magnetic field in which it is placed.

The Intensity of Induced Magnetisation which soft iron can acquire under induction tends to rise to a maximum limit. This limit is called the **Limit of Magnetisation**; and a bar magnetised up to this limit is said to be "**saturated** with magnetism" or "magnetised up to its full capacity for magnetism." The reason for the existence of such a limit appears to be that the process of magnetisation, *i.e.* of turning the already magnetised molecules of the iron round into the same direction, is then completed, and there are then no molecules to be turned into position.

If we estimated the strength of a current by means of the suction of a soft-iron bar into a current-bearing solenoid, the result would not be suitable for the measurement of large currents, because the induced magnetisation of the soft-iron bar is not quite proportional to the exciting current, and the readings of the instrument are not quite proportional to the square of that current: but this difficulty is got over in **Ayrton and Perry's Ammeter** (*i.e.* Ampère-meter) by using, not a soft-iron bar, but a very thin **soft-iron tube.** In that case the thin tube very soon reaches its limit of magnetisation; and when this limit has been attained, the magnetic strength of the tube remains constant; and the pull upon the spring is then **directly** proportional to the number of Ampères, not to the square of that number. For small currents a soft-iron bar does well enough: and in that case we may find what the suction of the bar into the coil is by balancing it against the weight of known masses from a "box of weights," as in the **Electrical Storage Co.'s Ammeter.** Or, as in **Schuckert's Ammeter,** we may see how much this suction into the magnetic field of a spiral current will displace the bob of a pendulum, which bob consists of a mass of soft iron.

(*e*) The Physiological Effects of a Current

We need merely mention here that Current Electricity was first discovered through an accidental observation by Galvani that the contact of two metals with the nerve of a frog's leg made the muscles twitch. The student will become familiar with the physiological effects of a current in later stages of his study. Intermittent currents produce contractions and relaxations of a muscle; rapidly intermittent currents produce tetanus.

We have thus stated the principal properties and effects of a Steady Current of electricity, and shown, in passing, how these properties may be used as means of **measuring** the **strength** of the current.

When once we know that a current is of a certain strength, it **does not matter** in the least what its **source** was; it might have come from a small cell, or it might have come from the electric mains of a town and been reduced by the interposition of suitable Resistances; or it might have come from a frictional machine worked continuously without sparks, or from a sufficient thermo-electric pile. If the **strength** (and, it may be, the fluctuations of the strength) be the same, the **effects** in and near the conductor along which the current passes will be **the same.**

But a **medical man** who applied an electric current without knowing its Strength would be working in the dark: he must always **measure his currents** by an Ampère-meter or rather by a **milliammeter**, which measures from 1 to 300 thousandths of an Ampère.

Quantity of Electricity

We may recall the definition of **strength of current** as the **quantity of electricity** which is supposed to flow past any given point of the conductor **during each second**: and we must now ascertain what is meant by the expression "Quantity of Electricity."

Quantity of Electricity.—A Current may in particular cases be uniform; it may be kept up, as it is when a galvanic cell or battery is used as the source; but the distinctive constant condition of the neighbourhood of a wire in which a "steady current" is passing, and the continuous evolution of Heat in a wire or the continuous Chemical Decomposition of an electrolyte through which a "steady current" is maintained, do not help us directly towards the idea of a "**current.**" That concept comes from another part of the subject, namely, the **discharge** of a "**charged**" body through a **wire.** Let a body be "charged" or "electrified"; we may connect it with the nearest gas or water pipe, or otherwise bring it into communication with the earth, as by means of a long thin wire ; its charge will disappear ; it is said that it escapes to earth along the wire ; but the important point to note is that during a very brief period of time that wire presents all the phenomena of a current-bearing wire. If we use an exceedingly long and thin wire we may protract the time which the charge takes to escape : we are therefore in a position to measure the strength of the current at successively equal intervals of time ; and from this we get data which enable us to calculate what the original charge or quantity of electricity must have been : for the Strength of the Current, considered as a rate of escape of electric Charge or Quantity, depends on what that Quantity had originally been.

When we compare the strength of the current, so obtained, with the strength of the current through the same wire from a galvanic cell, we find that the Current-Strength or rate of flow in the case of a galvanic cell is far greater than in the case of any ordinary charged or electrified body ; and therefore the Quantities of Electricity with which we have to deal in the former case are far greater than they are in the latter.

One consequence of this is that the Practical Unit of Quantity, with which we have become acquainted under the name of a Coulomb, is far larger than the Unit of Quantity to which we are led when we contemplate only the phenomena of charged conductors and their discharge through wires. The latter unit is called the C.G.S. electrostatic unit ; and the Coulomb is equal to 3,000,000,000 C.G.S. electrostatic units. If we were to measure the electric quantities, with which we usually have to deal in electric currents, in C.G.S. electrostatic units we would have to use the most inconveniently large numbers. But the student must take care not to confuse the Coulomb, which is used as a practical unit of quantity, with the C.G.S. electrostatic unit of electric quantity, of which we shall soon reach a definition.

If we put a piece of glass and a piece of resin together, we find after pulling them apart that they attract one another. If we use two such pieces of glass and pieces of resin we find that either piece of glass is attracted by either piece of resin; but that the two pieces of glass or the two pieces of resin repel one another. This may be ascertained by suspending these objects on thin silk threads; if they attract they approach one another, when sufficiently near to one another to make the phenomenon manifest; if they repel they recede from one another, and the suspending threads diverge. These bodies are therefore in a condition differing from that in which they were before the rubbing; they are said to be "electrified." Similarly electrified bodies repel one another; dissimilarly electrified bodies attract one another. The Ether between the electrified glass and resin is in a stretched condition, the same as that which has been already described in reference to the Ether between the two terminals of a Galvanic Cell.

A body may be very feebly electrified, as by a very little very gentle rubbing; or it may be more highly electrified, as by firmer rubbing in very dry air. A body more or less highly electrified is thus said to be more or less charged with Electricity, to bear a greater or less electric charge, or to possess or be charged with a greater or less Quantity of Electricity. We thus find that bodies may vary in their electric charge, and it is necessary to have a standard, for the sake of measurement of this electric charge or quantity of Electricity. This standard is the so-called Unit of Electric Quantity. In order to reach such a standard, advantage is taken of the further observation that the attraction or repulsion between two electrified bodies diminishes as their mutual distance increases; and the law is that the Attraction or Repulsion varies inversely as the square of the distance between them. Then, again, the more highly a body is charged, the more powerfully is it attracted or repelled, and the more powerfully does it attract or repel. On the whole, the phenomena may be brought together and summarised by the formula that the Force of Attraction or of

Repulsion, in dynes, is equal to the **Charge** on the one body multiplied by the **Charge** on the other body, divided by the *square* of the **Distance** between them.

Then, what would be the Unit of Charge or of Quantity? Suppose the Force was one dyne: and also that the Distance was one centimetre; then the product of the two Charges will be equal to 1; and if they are equal to one another, they are such that the figure 1 is the proper number to employ in reference to each of them: that is, each is a Unit-Charge.

Thus we arrive at the definition of the Unit of Electric Charge or the **C.G.S. Electrostatic Unit of Electric Quantity**; this is a quantity such that, if **two** small bodies be **each** charged with it, and placed at a mutual distance (between their centres, in air) of **one centimetre,** they will attract or repel one another with a Force equal to **one dyne.**

Such, then, is the C.G.S. Electrostatic Unit of Quantity; but it may now be noted that it is founded on a mere **convention.** It is agreed, because it is found to be convenient so to do, to speak of Electricity as a thing, a kind of **imaginary matter,** which may be distributed as a film on the surface of a charged body, or which may run along a wire and thus escape from a charged body to the earth. We say that this imaginary matter attracts or repels other electric matter, equally imaginary, according to laws quite analogous to that of Gravitation in reference to ordinary Matter; but all this is merely a mode of stating the observed **forces** in the region surrounding an "electrified" body, that is in the "**Field of Electric Force**" surrounding that body. This mode of statement serves its purpose very well: and perhaps if more accurate phraseology were adopted, and everything referred at once to strains and stresses in the Ether, the language which would have to be employed would not be intelligible to the beginner. We must therefore go on unhesitatingly, using the language currently in use, and referring electrostatic phenomena to distributions and attractions of this **imaginary electric matter**, with occasional digressions to explain how the same phenomena may be otherwise accounted for in terms of disturbances and local conditions in the Ether.

In the first place, then, this imaginary electric matter may be + or −, **positive** or **negative**. Certainly a piece of **glass** rubbed with resin is in a **different condition** from the piece of **resin** on which it has been rubbed; for the former will attract while the latter will repel a piece of resin, similarly rubbed on glass. Therefore the glass is said to be charged with **vitreous** and the resin with **resinous** Electricity; and it is found that if any body be electrified at all, it must be charged either with Vitreous or with Resinous electricity. We thus have only **two** "Kinds of Electricity" to deal with. But further, if a body charged with resinous and another **equally** charged with vitreous electricity be brought into contact, the charges of both apparently disappear, and the bodies resume a **neutral state**. To add a quantity of vitreous to an equal quantity of resinous electricity thus leads to the absence of electrification, just as the addition of $+x$ to $-x$ in algebra gives a result which is equal to zero; and thus Vitreous and Resinous Electricities bear to one another the same relation as Positive and Negative quantities in Algebra. Which is, however, the positive and which the negative? This we do not know; but it is agreed that we shall call the **vitreous "positive,"** and the **resinous "negative."** Therefore we say that when a piece of resin is rubbed on glass, the glass acquires a positive and the resin a negative charge. Our adjectives might, however, have been reversed without affecting our results.

When a body is charged, and if it be a conductor of electricity, the charge is distributed **only over its surface**. Inside the conductor there are no electrical phenomena at all. In Faraday's **ice-pail experiment**, a charged body was let down into the interior of a hollow metal vessel, and allowed to touch the side or bottom: the whole charge of the charged body disappeared, but was found distributed on the outer walls of the metal vessel surrounding it. So long as the body A did not touch the walls of the vessel it retained its charge, but lost it when it touched the vessel B.

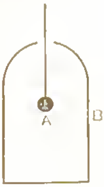

Fig. 268.

In the language of the Ether-stress theory we would say: Round the electrified body there is a region or **field of electric force** in which the Ether is subjected to Stress. At each point the Ether-stress has a particular amount and line of action. At any one point in the field, a small electrified body would, by reason of the stresses in the Ether, be drawn or driven in some determinate direction with a determinate Force. It would be drawn or driven away from the point in question along some Line passing through that point: and if we traced out its subsequent movements, we would find that its course had been mapped out for it before it came into the field, and that it followed the trend of what are called the **Lines of Electric Force** in the Field. These are lines which show at each point the direction in which an electrified body would tend to travel if it were brought into the field and were allowed to move freely under the influence of the existing Forces there. Fig. 269 shows these Lines of Force in the neighbourhood of a small charged body in a large space: the attractions and repulsions are at all points practically straight from or directly towards the charged body. Fig. 252, p. 400, also shows the Lines of Electric Force in the neighbourhood of two oppositely charged conductors; a positively charged body placed at any point in the field would not travel straight towards the negatively charged body, but would take a devious path, along the local Line of Force, in order to reach the negatively while at the same time avoiding the positively charged body. These Lines of Electric Force are **oppositely directed** at their **two ends**, much as a piece of stretched indiarubber pulls one way at one end, and the opposite way at the other. The Lines of Force terminate on the **surface** of a conductor and **do not penetrate** it: and they thus have **free ends** on the surface of any conductor which they may encounter.

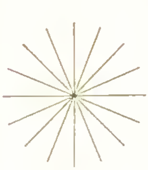
Fig. 269.

But where there are Free Ends of Lines of Force, there and there only is there what we call a distribution of **electricity**, or of **electrical quantity** or **Charge**. These Lines of Electric Force are themselves somewhat arbitrary means of setting forth the **forces** actually existing in the field; but they serve to emphasise the fact that the phenomena are not phenomena of the bodies moving in the field, but of the electrostatic **field** itself, that is to say, of the Ether surrounding the charged bodies. It will not be difficult to understand, from the analogy of a band of indiarubber, that each and every Line of Force must necessarily have **two ends**; that if the essence of the phenomenon is that the Ether is subjected to Stress, it must be stressed between **two points** at least; and hence, if any body be "**charged**," this means that at the Surface which is said to be charged there is **one free end** of the corresponding Line of Force. Then the **other end** of that line must be somewhere; whence the following proposition.

For every given charge of Electricity on any charged body, there must always be an **equal** charge of the **opposite electricity** somewhere.

Thus, when a little **pith ball**, charged positively, is hung upon a silk thread within a room, the equal and opposite negative charge will be found on the **walls** of the room, and the space between the charged body and these walls is a Field of Force. If the charged body be out in the open air, the opposite charge is on the surface of the earth and, it may be, upon neighbouring clouds or even on the surface of the heavenly bodies, distant though these be.

The **stress across the Ether** is measurable. In the neighbourhood of a charged conductor it is as if the Ether were made up of strings or cords, each of the shape of the corresponding Line of Force, and all stretched; so that these cords or lines of force tend to **shorten** themselves and to push each other aside. The lines of force therefore **repel each other**. These two tendencies on the part of the Lines of Force, to shorten themselves and to repel each other, account for all the movements of electrified bodies in the Field of Electric Force.

Where the Forces in the field are greater, we figure to ourselves the Lines of Force as being more crowded together; and it is agreed to suppose them present in just such numbers that where the **mechanical force** on a unit of electrical quantity—not the Coulomb, but the **C.G.S. unit of quantity**—is one **dyne**, there is **one line of force** to be found crossing that region **per square centimetre** of area, this area being set off at right angles to the direction of the lines of force themselves; and so on in proportion. In the field as thus represented, the direction of the lines of force shows the **direction** of the Forces acting on a unit-quantity of electricity at any point, and the relative crowding together of the lines of force shows what is called the **strength** or Intensity of the **field of electric force**, *i.e.* the value, in dynes, of the Force acting upon a Unit of Quantity when placed there.

When a body charged with a C.G.S. electrostatic unit-quantity of Electricity is put at some point in the field, say at a place where the Force acting upon it is one Dyne, and is then allowed to move a certain distance, say one Centimetre, a certain amount of **work** is done upon it, in that case one Erg; then in driving the charge from the one position to the other, one Erg of **potential energy** is **sacrificed** by that electrical system which consists of the attracting and the attracted, or the repelling and the repelled bodies, as the case may be. Let us now take the unit-charge away from the field, and look at the **field itself**; let us consider the **two points** which formed the beginning and the end of the path of the body moved. We might describe these two points by saying that they are, relatively to one another, in such **conditions** that *if* a unit-charge were placed at the one the system would have one unit of Potential Energy more than if that charge were placed at the other; and we might express this briefly by saying that the one point is at a higher "**Potential**" than the other, by one unit. The **Difference of Potential** between the **two points** measures the **work** done upon the **unit of quantity**, when it is allowed to travel freely from the one point to the other in obedience to the existing Forces in the field; conversely, it measures the Work which must be done *by* exterior forces in order to make the unit-charged body move from the point of lower potential to the point of higher potential against the Electric Forces in the field; and the Work done by or against the electric forces, when a body bearing any charge, Q units, is moved from the one point to the other, is equal to the product of Q into the Difference of Potential.

The Difference of Potential between two Points is a matter of importance throughout the theory of Electricity. Mainly is it so for this reason, that if by any means a difference of potential has once been set up between any two points, and if a conductor bearing a charge of electricity be laid across from the one of these points to the other, the charge on the conductor so laid across will **alter in its distribution**; it will tend to accumulate towards the point of lower potential; in order to effect this, it will **flow**, and there will be a **current** of electricity along the conductor. A Current of Electricity along a Conductor is therefore due to a Difference between the Potentials at its extremities. The difference of potentials between any two points may be itself ascertained and may be measured, in Volts or in C.G.S. units as we please, by finding out what the tendency is for the passage of a current along a conducting wire laid along from the one point to the other; that is by measuring the Current which actually passes in a wire of known Resistance. The principle is the same both as between two points in an Electrostatic Field, and between two points of a Galvanic Circuit, though this method is not by any means the most suitable in the case of an electrostatic field, because the current produced is so brief in its duration. In an electrostatic field, the effect of laying a wire across from the one point to the other is to **equalise the potential** of the two points, and the current by which this is effected is extremely brief and small in quantity; but in a **continuous** Current the Difference of Potential between any two given points of the conducting wire is **kept up**.

When our aim is to measure the Difference of Potential between two bodies according to electrostatic methods, we must find out what the Mechanical **force** or Traction is **across** an electrostatic **field** between two plates at a known distance apart, which plates are respectively brought to the same potentials as the two bodies to be tested; and from this the difference of potentials can be calculated.

Difference of Potential is analogous to Difference of Temperature, and determines a **flow** of Electricity as the other determines a Flow of Heat.

The expression "The Potential at a Point" is sometimes made use of. It seems as well to explain this. We can experimentally know nothing about Potential except as a difference of potential between two points, and we know **nothing** as to the **absolute value** of the Potential at any one point. If we did know anything about this, it would be the difference of potential between the point in question and some other point wholly remote from any electric influence whatsoever; for example, a point at an **infinite distance** from all electrified bodies.

Hence we have The Potential at a point defined as the number of Ergs of **work** which would be done by a repelling system in repelling a **unit-charge** to an **infinite distance**, or which would have to be done in bringing up a repelled unit-charge from an infinite distance to the point in question against the electric forces.

All we really can do however is to say what is, at any particular moment, the potential of the point in question with reference to the **Earth.** For all we know, the Earth may be electrically charged, positively or negatively; and perhaps its charge, if it have any, may fluctuate in accordance with the development of electricity elsewhere in the Universe, say on the occurrence of storms in the Sun. But we are not aware of such charges, or of their amount; our knowledge is all relative; we **assume** the **earth** to be in a **constantly uniform** electric condition; and we make the very arbitrary assumption that it has **no potential** at all. Then a body which is at the same potential as the Earth, that is, one from which no current flows towards the earth (or *vice versâ*) when that body is connected with the earth by a wire, is said to be at **zero potential.** All bodies from which a current flows towards the earth through a connecting wire are then said to be at **positive potentials,** while those in which a current flows from the earth towards the object on similar connection being made are said to be at **negative potentials.**

For example, in a dynamo circuit where the difference of potentials between the terminals is say 500 Volts, if the mid-point of the dynamo be at zero potential the terminals are respectively at potentials +250 and −250 Volts; and a person touching these with bare hands would have a current running through him to the earth, or running through him from the earth, as the case might be.

What happens during the redistribution of charge during a **brief current** of electricity may be understood from Figs. 270*a* and *b*. In Fig. 270*a* A is a body bearing a surface-charge of electricity, and very far from any surrounding objects. The lines of force radiate out from it practically as straight lines at right angles to its surface. In Fig. 270*b* there is brought up into the neighbourhood of A another body B, and A and B have been connected by means of a **wire**; the Lines of Force radiating from both A and B taken together are exactly the same in number as they were before, when radiating from A alone. They have however assumed **new positions**; each of them has taken up a different position in the field; and during the passage of the Current, each of them must have **slipped along**, transferring the stressed condition of the Ether along with it from one place to another. This enables us to understand how it is that during the passage of a Current, the Ether is the **carrier** of the **energy**, and that the conducting wire, if a perfect conductor, is really outside the phenomenon, which is confined to the Field of Force external to the wire. There is also a corresponding displacement of the lines of force at their opposite extremities, at the opposite boundaries of the field of force. While a continuous **current** is passing along a wire the Lines of Force go **slipping along** the surface of the wire with the **velocity of light,** and very few of them are present at any one point of the conductor at any one instant of time.

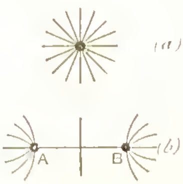

Fig. 270.

Take for example the case of a wire along which a current whose strength is one Ampère is passing. If the whole of the lines of force which pass any given point in a second—that is, the number of lines which correspond to one Coulomb, or 3000,000000 C.G.S. units of quantity—were present in the neighbourhood of that point at any one time, the Forces would be prodigious, and sparks of enormous length would be produced. But the electrostatic forces in the neighbourhood of a wire bearing a current of electricity are very small; the Ether does not transmit more Energy to any given point of the conductor than is instantaneously taken up and transformed either into Heat, into the energy of Work, or into some form of Energy other than that of electric condition of the wire, or rather, that of electric stress of the field itself.

If a body be charged and placed upon an "**insulating**" support, that is, a support made of a material which does not conduct electricity, it has no means of losing its charge, and retains it for a very long time. Not indefinitely, however; for there is no substance which is entirely destitute of conducting power, and the air itself, through bringing dust and depositing moisture upon the insulator, causes deterioration of its insulating qualities. The most ordinary form of **insulator** is a glass or sealing-wax rod, carefully dried and, if need be, sheltered under a protective glass case. A partial vacuum is not favourable to insulation, for it has itself some conducting power; a good vacuum, on the other hand, is a good insulator.

When a person is made to stand on a stool with glass legs, he may be very highly charged with electricity from a frictional machine, so that the hairs of his head may, being similarly charged, repel one another, and stand erect: and if another person standing on the ground touch him, the charge will escape with a spark. If these sparks be taken off the bare skin, weals may be produced, resembling an eruption. In extremely dry climates, a person standing on a thick carpet may so far charge himself with electricity by rubbing his feet on the carpet that he can light the gas by bringing his finger near the burner; for a spark then passes.

At the same time, it has to be noted that there does appear to be something of the nature of loss of electric charge by Radiation, which is hindered or prevented by surrounding the charged body by a metal sheath or by yellow glass.

Even if supported in air upon a good insulator a body will not take up an **indefinitely great charge** of electricity.

It cannot be charged at all, in air, so as to have a charge exceeding 103 C.G.S. units per square centimetre. When that is the case the stress across the air in the neighbourhood of the conductor is 66,708 dynes per sq. cm., and there is a discharge by **spark** across the air. Much smaller densities of charge than this will cause sparks to fly across the intervening air between two oppositely charged conductors brought near to one another.

Capacity.—When a conductor which is charged with Electricity is brought into contact or into metallic communication with another which is uncharged, or not charged to the same potential, then, if the two conductors be exactly similar and similarly situated with respect to one another, the Charge, or the sum of the charges, will be **equally divided** between them ; but if they be unequal in size, or be unsymmetrically situated with respect to one another, the Charges borne by each respectively after they are moved apart will **not be equal**, though **both conductors** have come to the **same potential**. In the latter case, to bring the two conductors to the same Potential requires different amounts of Electric Charge ; and the one of the two which requires the greater share of the joint charge in order to equalise its Potential with that of the other is said to have the greater **Capacity** for Electricity.

The **work** done in charging a conductor is, in ergs, equal to *half* the product of the Charge into the Potential acquired. We might have expected it to be the product and not half the product, for when a Current passes, the Work or Energy is, in Joules, the product and not half the product of the Ampères into the Volts into the Time—that is, it is the *product* of the Coulombs into the Volts : but it will be observed that as we go on charging a conductor, the **potential**, which is at first nothing, goes on **steadily rising**, so that we encounter a steadily increasing Resistance to further charging ;

and the Average Resistance to charging, the average tendency to a back-flow, which we have to overcome in consequence of the existing potential, is equal to the **average potential** during the charging; and this average potential overcome is **half** the potential ultimately attained. If the charge be allowed to escape to earth along a wire, the quantity which escapes travels under steadily diminishing potential; so we again see that the Work which we can get out of a charged conductor pure and simple by discharging it through a wire is equal to the product of the average potential into the quantity allowed to escape; that is of *half* the maximum Potential into the Quantity. In a **steady current**, on the other hand, the Potential in the circuit is kept up, and remains steady during the working of the battery; so that in this case we have the Energy liberated measured by the product and not by half the product of the Ampères into the Volts.

In the case of Steady Currents we may look for an analogy in a stream of **water** flowing in a water-pipe; there are two respects in which such streams may differ, the **quantity** of water which flows and the **pressure** at which it is supplied. A stream of water small in quantity but supplied at a high pressure may deliver the same amount of Energy per second as a stream larger in quantity but supplied at a lower pressure; and the analogue of the Rate of Flow of water is the **Ampères**, while that of the Pressure is the **Volts**. In fact, the Voltage is often spoken of as the Electric Pressure; and thus we hear of high-pressure and low-pressure currents. In some cases it is of advantage to supply currents at a high Voltage and a low Ampèrage; for the **loss of energy** by transformation into Heat on the way from a distant source is proportional to the square of the Ampères, and does not depend on the number of Volts. It is therefore well to keep the former low, but to keep the Energy, which depends on the product of the Ampères and the Volts, up to the mark by increasing the Voltage, that is, by delivering the current at a high electric pressure.

Electrostatic Induction

When a body A, charged with electricity, is brought near an uncharged one, B, it is found that the **end** of the body B which is **nearest** to the charged body becomes **charged** with electricity of a kind **opposite** to that of the charged body, while the **remote end** becomes **similarly** charged. If B be **touched**, the **similar** charge upon it **escapes**: and then if A and B are separated, A is found still to retain its original charge unaffected, while B has acquired an **opposite** charge, which it **retains**. Any number of **successive charges** may be induced in successive bodies similar to B, by similar exposure to the inductive action of the charged body A.

Fig. 271.

A Line of Force never penetrates a Conductor; and wherever a line of force has a **free end** on the surface of a conductor, the surface of that conductor is in a condition in which we say it has a Charge of Electricity. Let a small pith-ball, or the like object, be charged with electricity and isolated in an open space. The Lines of Force radiate from it as straight lines, equally in all directions, as in Fig. 269; and their other ends are to be sought for at the opposite boundaries of the field of force. Now let us suppose that we place around this charged body a **complete closed shell** of conducting material, say metal, and that we so arrange it that the **charged body** is precisely in the **centre**. The metal shell then produces no effect upon the lines of force, except to interrupt them to the extent of its own thickness (Fig. 272). The Lines of Force have **free ends** at the **inner surface** of the metal, and also at its **outer surface**. In other words, the metal bears on its **inner surface** a charge **opposed**, and the **outer** surface a charge **similar** in kind to that of the charged body. The number of lines of force is not affected, and the charge on the **inner** surface is **equal** as well as opposite to the charge on the charged body. The number of lines exterior to the shell is the same as it was at first, and the whole

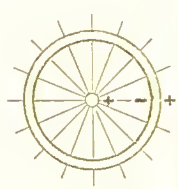

Fig. 272.

exterior charge is equal as well as similar to the charge on the charged body, the so-called "inducing" charge. The two "charges" inside the shell, the inducing and the interior induced, together produce no effect upon an external body; and thus the only "charge" acting upon any external body is the external induced charge on the shell. All this can be quite easily understood from the figure, Fig. 272; the original field is divided into two parts which are independent of one another. Naturally, therefore, any body external to the shell is only acted upon by the Lines of Force in the exterior field.

Again, if the exterior of the shell be touched, the exterior field is destroyed; for conducting communication is then set up between the shell and the earth: but the inner field is not affected by this, and it persists until such time as it in its turn is destroyed by contact being made between the charged ball and the shell. If this be done, all electrical charges disappear.

If again, while matters are in the condition of Fig. 272, contact be made between the charged ball and the inner surface of the shell, the inner field is destroyed and the outer alone remains; and then, as we can thereafter find no electrical charge within the shell, but find the original number of Lines of Force coming from the outside of it, we say that the whole of the charge has been transferred to the exterior surface of the shell. If the shell itself be already charged it makes no difference; the lines from the charged ball are all added to those already passing from the exterior of the shell: and thus we may, by successively touching the interior of such a shell (in which a small hole is made sufficient to admit of the insertion of the charged ball) with a ball charged with electricity, make a very strong external field. In this way we may, as is said, accumulate a considerable charge of electricity on the outer surface of the shell, thus raising it to a high potential.

If instead of an enveloping shell we take a cylindrical conductor (Fig. 271), the phenomenon is quite similar. The inducing charged conductor A has its lines somewhat concentrated towards the induced conductor B brought into its neighbourhood: where these meet B, its surface is oppositely charged; where they leave it, it is similarly charged: and on touching the induced conductor the part of the field farther from the inducing charged body is destroyed, and thereafter the induced conductor is found to bear a charge opposite to that of the original charged body.

This kind of phenomenon in the electrostatic field is utilised in the Electroscope, the purpose of which is to detect electrical charges and ascertain their nature, whether positive or negative. In this instrument, A is a glass vessel, closed by a vulcanite lid B, through which passes a metal rod C, surmounted by a metal disc D, and terminated by two slips of gold leaf E. The approach of an electrified body towards the metallic disc D causes a similar charge to be developed in the gold leaf strips E: but as these two strips are similarly charged, they repel each other and diverge. They thus indicate electrical charge in the body brought near D. If the disc D be touched with the hand, the charge of E disappears and the leaves fall together and remain together, so long as the inducing charged body is retained in its position. If, however, the charged body be removed, the induced opposite charge of D is distributed all the way from D to E. The leaves again become electrified similarly to one another, and repel one another once more. Let a body charged with a charge of electricity of unknown sign be now brought near the charged electroscope. If it be of the same sign as the original charged body, it will cause the leaves to collapse as it approaches from a sufficient distance: if on the other hand it be of the opposite sign, it will cause them to diverge still farther. The reason of this is the following. Suppose the original charged body was *positively* charged. Then the charge left in the electroscope after touching was, on the removal of the charged body, a negative charge. If a positive charge were brought near, it would tend to induce a positive charge in B which was already negatively charged: the result, at a sufficiently great distance, would be a fall-off in the divergence of the gold-leaf strips; at a particular distance there might be non-electrification of B; but the induced positive charge would tend, at closer quarters, to overpower the existing negative charge, and again there might be divergence. If a negative charge, a charge opposed to that of the original body, were brought near, the effect, at all distances, would be an increase in the divergence of the gold-leaf strips.

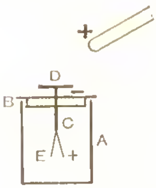

Fig. 273.

The practical rule for use of the Electroscope is therefore: bring up the charged body; observe the divergence; touch the disc and remove the charged body; then cautiously bring up from a distance a rod of sealing-wax rubbed with dry flannel or bearskin, this sealing-wax being then negatively charged: if the divergence of the gold-leaf strips increase, the electrification of the sealing-wax is of opposite sign to the original charge, that is to say, the original charge was positive; if it make the divergence diminish, the original charge was negative.

Induction is also utilised in the Electrophorus. This instrument consists simply of a plate of vulcanite upon which rests a disc of metal with an insulating handle. Remove the disc: beat the vulcanite with a dry and warm catskin; the **vulcanite** becomes **negatively** charged: lay the metal disc upon it; the metal is never perfectly in contact with the vulcanite and is for the most part separated from it by a film of air; its lower surface becomes positively and its upper surface negatively charged. Now **touch** the upper surface of the metal with the finger; the upper negative charge escapes, and now there is only left a very **thin** Field of Force between the vulcanite plate and the metal disc. Do Work upon this field of force by stretching it against the electrical forces in the field; that is, **lift** the disc away from the vulcanite plate. The result is that though the Quantity of positive induced charge on the metal disc cannot increase, the **potential** of that charge becomes very high, and now the finger, applied within a short distance of the metal disc, may draw a **spark** from it. Small original charges may thus give rise to successive charges of high potential. In some of the best electric machines the same principle is applied, with this difference, that the contrivance is so devised as to act **continuously** by rotation, instead of intermittently as in the electrophorus (Holtz machines).

In **Electrostatic Condensers** we have an application of the properties of Electrostatic Fields of **limited dimensions**. Suppose a charged spherical body: it does not matter whether this be solid or hollow, for lines of force cannot in any case penetrate the surface of a conductor. Let this be charged: lines of force pass away from it to the very distant boundaries of the field of force. Now surround this with a concentric shell: as in Fig. 272, we produce an inner and an outer field of force. Now destroy the outer field: we then have only an inner field, annular on cross-section. The Capacity of this inner field, or of the conjoint system of concentric spheres, is greater than that of either of the spheres taken alone: and the underlying reason of this is that we are dealing with a more limited field of force, in which there must be larger charges before we can get up equal differences of potential (Fig. 274).

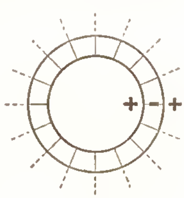

Fig. 274.

This kind of apparatus is to some extent realised in the **Leyden jar.** In this instrument we have a glass jar lined internally and externally (not quite to the top) with tinfoil. Inside there is a chain, or some other means of causing metallic communication between the inner tinfoil and a metallic knob situated above the cork which closes the top of the jar. The inner tinfoil may be **charged** by contact of the knob with a charged body or some source of electricity: the interior charge produces a **field of force** which extends **through the glass** to the outer tinfoil and beyond it exteriorly after the fashion of Fig. 274. In other words, the outer tinfoil bears an opposed charge interiorly and a similar charge externally. We get rid of the latter, destroying the exterior part of the field, by connecting the outer tinfoil with the earth; and we then have left simply that limited **field of force** which lies **between the two tinfoils.** In this limited field of force the electric stresses are not through air but **through glass.** If we charge a Leyden jar with a given quantity of electricity, the potential attained is small; but if we charge it to a given potential-difference, as we may do if we connect it with the terminals of a powerful galvanic battery or a frictional machine, the quantity of charge which it will take up is relatively great, because the electrostatic capacity of the limited field is high.

When a condenser has to be discharged, a pair of **discharging tongs** may be used. This is a metal rod terminated by brass knobs and supported by an insulating handle of glass. One of the knobs is laid on one of the coatings and the other knob is brought into metallic communication with the other: the field of force is thus discharged, with the production of a **spark.** This spark, though apparently instantaneous, in reality consists of a vast number of electric **oscillations** which follow one another with waning vigour. The rate of oscillation depends on the size of the jar and on the resistance offered by the wire which connects the opposed plates; but the **frequency** may be stated, with a pint Leyden jar and a pair of discharging tongs, to be about **two million** per second. This violent oscillatory shattering produces a peculiar effect on any part of the human body through which a Leyden jar may be accidentally or of set purpose discharged. This discharge may occur when the knob is **touched**, for then the arm, the body, the earth and the table, play the part of the discharging tongs and the discharging current passes through them. To prevent accident of this kind it is advisable always to apply the discharging tongs to the outer coating first, and then to the knob.

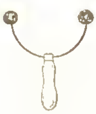
Fig. 275.

Leyden jars may be arranged in **batteries**, and there are two main ways of doing this. The first is to connect **all the inner** coatings and **all the outer** coatings respectively: this virtually makes one great Leyden jar of increased surface and correspondingly increased capacity. The second is to connect the **outer** coating of the **first** with the **inner** of the **next** and so on; the **inner** coating of the **first** is **charged**; the inductive effect runs down the series of jars, and the Potential of the whole battery is the difference between the potential of the first inner coating and that of the last outer coating; but the advantage is that a given potential-difference is distributed among a great number of jars, so that no one jar has its glass subjected to too great a mechanical stress across the field of force, and the **risk** of spoiling a jar by **perforation** of the glass is obviated.

The **capacity** of a **condenser** is equal to $\frac{K}{12\cdot5664}$ × (surface ÷ distance between the plates). In air K = 1; and therefore the capacity of a flat condenser consisting of two opposed plates, each of area say 100 sq. cm., at a mutual distance of $\frac{1}{4}$ cm., would be $\frac{1}{12\cdot5664} \times 100 \div \frac{1}{4} = 31\cdot831$; and to bring its plates to a potential-difference of 1 C.G.S. unit (or 300 Volts), 31·831 C.G.S. units of charge would be required. But if other substances than air intervene between the opposed plates, K has other values; if a slab of sulphur were interposed between the plates instead of air, then instead of 31·831 units being the quantity required for this purpose, the quantity necessary would be 3·2 times 31·831, that is, 101·86 units. The letter K in the formula has for sulphur a value equal to 3·2; and this is what is called the **specific inductive capacity** of sulphur. Other substances give us different numbers; so that each substance has its own Specific Inductive Capacity; and for convenience that of **air** is taken as a **standard** of comparison, and is said to have a value = 1. In the higher study of Electricity, this property of each substance is of considerable importance; but it is not proposed to follow up its consideration in this place; let it suffice to say that the particular inductive capacity which Air happens to have plays a part in determining the value of the Forces in the field, and indeed the value of all numerical data throughout the facts of Electricity: and that all our statements apply, unless otherwise stated, only to the case where **air** is the medium in the Field of Force.

Production of Difference of Potential

What the electrician sets himself to do when he means to produce a Current of electricity, or to produce the phenomenon of the Electrostatic Field, is really to produce Difference of Potential. Such difference of potential may be produced in many ways: but we can hardly explain the real nature of any one of the methods. We shall however now state the principles of the methods employed, under the following heads:—

I. Electrification by contact of non-metals.
II. Electrification by contact of metals.
III. Galvanic-cell methods.
IV. Thermo-electric methods.
V. Dynamo-Electric Machines.
VI. Friction of water against steam or air.
VII. Evaporation.
VIII. Pressure.
IX. Heating.
X. Electro-capillarity.
XI. Electrification by Flames.
XII. Physiological Currents.

Of these the first five are the most important.

I. **Contact of Non-Metals.**—How it comes to be that a piece of glass laid in contact with a piece of resin becomes positively charged while the resin becomes negatively charged remains at present wholly unexplained; what the relation of the glass, the resin and the intervening Ether, or the relation between either the glass or the resin and the surrounding Ether before contact may be, we do not know. We must be content in the meantime to accept it as a fact that there is a Difference of Electric Condition between the glass and the resin: and we infer that there is a Stress across the Ether. Different substances act differently in respect of the degree of electrification set up: and in the following series the substances first named become positive to those following them, negative to those preceding them, when brought into contact: Cat and Bearskin—Flannel—Ivory—Feathers—Rock Crystal—Flint Glass—Cotton—Linen—Canvas—White Silk—the Hand—Wood—Shellac—the Metals (Fe, Cu, Brass, Sn, Ag, Pt)—Sulphur—Soapstone. **Mere contact** however produces a very **small effect**, for the points of contact are always in reality very few; and **friction** increases the effect by multiplying the points of contact. Hence the one substance is in practice always rubbed on the other: and one of the most convenient means of producing a small charge of high potential is to rub sealing-wax (shellac) with dry flannel, and then to use the sealing-wax as a body charged with negative electricity. The potential is high because the charge is confined to the points which have actually been in contact; and there is no diffusion of the charge, and consequent lowering of the original potential, by any spreading of the charge over the surface.

Metals (if duly insulated) may be charged in the same way; but the potential is less, for not only is the charge, which is generated at the points of contact, spread over a larger area by conduction along the surface, but the metal conducts back electricity so as to produce partial discharges during the process of rubbing. Again, a difference of potential is developed not only between surfaces of different substances but also between surfaces of the same substance in dissimilar conditions: so that the production of Electricity and the transformation of Electrical Energy into Heat is probably a phenomenon of constant occurrence in every case of Friction.

A stick of sealing-wax rubbed with flannel serves as a means of producing small charges: but the same result may be more conveniently attained on a larger scale by the continuous working of a "frictional electric machine."

In this a glass or vulcanite disc or cylinder is continuously rotated on an axle, and rubs against a silk rubber or rubbers. The glass or vulcanite rubbed becomes positively and the silk rubbers become negatively charged. The charge of the silk rubbers is allowed to escape to earth through a metallic chain: and in order to facilitate this escape the conductivity of the silk rubbers is improved by anointing them with a mixture of fat and metallic mercury. The positive charge cannot be taken directly off the rotating glass or vulcanite, for its surface is non-conducting; and an ingenious device is resorted to in order to get round this difficulty. A comb-like series of sharp points of metal almost touches the disc or cylinder as it rotates: the ends of the points, near the rotating disc or cylinder, become negatively charged by induction, while the back of the comb becomes positively charged; or rather, it would become positively charged were it not for the fact that this back of the metallic comb is itself metallically connected with some object which is to be charged by the machine, so that it is this object and not the back of the comb which becomes positively charged. This object may be either a large cylinder of metal or else a shell of metal surrounding the working parts of the machine, in which latter case the back of the comb is made to communicate with its interior; or it may be the inner coat of a Leyden jar, or the inner coat of one of the jars of a battery of Leyden jars.

When the object charged is a plain metal or metal-coated cylinder or metallic shell, it is called a "conductor"; a name which is more or less apt to lead to confusion.

If this conductor be connected by metal with the chain from the rubber, a Continuous Current of electricity, of very small current-strength, will pass in the connecting metal: but if the rubber be connected with a metallic ball and this ball be brought near the conductor, a torrent of **sparks** will pass through the gap between the two. If a Leyden jar or battery be used instead of a plain conductor, the sparks will be longer.

II. **Contact of Metals.**—When two metals, say copper and zinc, are brought into contact, they become electrified. The **copper** becomes **negatively** and the **zinc positively charged.** The student must not suppose that this statement in any way contradicts the former one that in a Galvanic Cell the terminal connected with the copper is the positive terminal, for we shall presently see how the one statement is connected with the other. **Copper** is therefore said to be **electro-negative** to **zinc**: and for each surrounding medium it is possible to arrange the metals in a series running from the most electro-positive to the most electro-negative. As the surrounding media vary, the order of the terms in such a series may also vary; which shows that the phenomenon depends in some way upon **chemical action** between the metals and the gas or liquid in which they lie. The modern explanation of what happens is the following. **Copper** surrounded by air is **always negative** to the **air**; **zinc** surrounded by air is **also negative** to the **air**, but **more so than copper** is, by about $\frac{3}{4}$ Volt.

When the copper is brought into **contact** with the zinc, their **potentials** become **equalised**: but the air in the immediate neighbourhood of the zinc and that in the immediate neighbourhood of the copper come to different potentials, so that across that **air** there is a **field** of **force** between the two metals. The air in the neighbourhood of the zinc is positive to that in the neighbourhood of the copper. Now separate the zinc and the copper: there remains a Field of Force across the air between the separated pieces of metal: and this we express by saying that the zinc is positively and the copper negatively charged.

The Field of Electric Force in the air is **maintained**, through the air being a **dielectric** or Non-Conductor.

The result will be precisely the same if the two metals, instead of being put in direct contact, are connected by a **metallic wire** or rod; and it does not matter of what metal the wire is made, nor even whether the connecting wire or rod is made up of one or of more metals: the Field of Force is that between the two **terminal metals,** even though local fields of force may have been set up between the different metals which make up the connecting wire.

Suppose that the air was a **conductor**; it would be impossible to maintain such a Field of Force in it, and the whole system would revert to its original condition, in which each metal stood at its own potential and the air was all at the same potential.

III. **Galvanic Cells.**—Next, instead of air let us use a **conducting liquid,** such as dilute sulphuric acid. The copper is again negative, say by x volts: the zinc is again negative, by about $(x+1)$ Volt: the acid is all at the same potential. Now **connect** the copper and the zinc by a wire: the copper and the zinc come to the same potential and a Field of Force is formed **in the acid,** as formerly in the air, but with a potential-difference across it of about one Volt. Only for an instant, however: the Field of Force is

broken down and a brief **current** passes, the Energy of which is originally derived from the energy of a trifling amount of solution of the zinc. This current runs across the Field of Force in the direction Zinc to Copper. But the Field of Force is instantly **restored** at the expense of the energy of a further amount of combination of the zinc, and it is as promptly **discharged**. The field of force thus being set up and broken down, the Energy of combination of the zinc with the salt-radicle of the acid to form sulphate of zinc becomes liberated as the energy of a Continuous Electric Discharge through the liquid from the zinc to the copper, with an accompanying **current** along the **wire** in the direction **copper to zinc.**

Polarisation.—In action, a **one-fluid** Galvanic Cell is subject to a **gradual decay** of the **current** produced by it, due to the following cause. The current takes positively-charged hydrogen-atoms towards the copper plate; these positively-charged atoms ought at once to coalesce and form bubbles, giving up their positive charges to the service of the general circuit; but they do not do this promptly; up to a certain limit they fail to agglomerate, they retain their charges, they linger in a charged condition about the copper plate, and they tend to repel the approach of other positively-charged hydrogen-atoms. They thus obstruct the current: they diminish its strength. Various devices have been adopted to get rid of this effect, which is called **Polarisation**; the means adopted are either to get rid of the hydrogen **mechanically**, as by rubbing or blowing it off or by making it deposit upon a very much roughened plate instead of a fine one (as in Smee's cell, in which platinised silver is employed), and thus to induce it the more readily to agglomerate into bubbles; or to get rid of it **chemically**, as by the device adopted in Daniell's and Grove's or Bunsen's cell, already described.

In the former of these the hydrogen is got rid of by being made to do work on a solution of sulphate of copper and to reduce it to sulphuric acid and metallic copper, which is deposited on the copper of the cell. The deposit of this metallic copper instead of hydrogen upon the copper plate presents no disadvantages, and there is no loss of power in the cell by reason of any Polarisation. In Grove's or Bunsen's the hydrogen is dissolved by nitric acid, with formation of nitric peroxide or nitrous acid: the products are, however, corrosive poisonous fumes.

Two-fluid cells are usually preferable for medical work; for in one-fluid cells the decay in the current, due to Polarisation, is apt to be very troublesome.

In Remak's modification of the Daniell cell, for medical purposes, with constant current, the copper forms a rosette at the bottom and is surrounded by a solution of copper sulphate, with crystals of the same: then a porous bowl is inverted over it, and is covered with paper pulp which supports the zinc. The zinc is covered with water merely: but when the circuit is closed the sulphuric acid diffuses through the porous bowl and paper pulp, and attacks the zinc.

A simple effect of Polarisation is well marked in **electrolysis**. The separated components, or Ions, of the material electrolysed are themselves **charged**; and as they accumulate on their respective electrodes they **repel** the next-coming particles of their own kind, because they are similarly electrified. They do this up to a certain **limit**; and if we attempt to electrolyse an electrolyte under too small a Voltage, the result is that we simply load the electrodes with these charged ions; and these bring the Electrolytic Conduction to a **stand-still**. Before the electrolytic conduction can go on, the oncoming ions must be propelled towards the electrodes with a force sufficient to overcome this repulsion; and therefore the current cannot continue to pass unless the **voltage** across the Electrolyte exceed a certain limit. The voltage of a single Daniell cell is not sufficient to cause the electrolysis of acidulated water; that of a Grove cell is.

If now the electrolysing current be stopped, there is a tendency for these accumulated ions to disperse, and to form a **reverse current** in the electrolyte and round the circuit. This circumstance has been utilised in the so-called **Storage Cells**, or Secondary Cells.

In these the electrodes are so constructed as to **exaggerate** the tendency to Polarisation, through their **structure** (spongy lead), or even to favour the establishment of **secondary reactions** which render the electrodes **different** instead of similar in character. For example, let the electrodes be each made up of reduced lead, or of red lead, or a mixture of litharge, red lead and lead sulphate, packed into a framework or grating of lead; then when a current is passed through acidulated water by means of such electrodes, the hydrogen liberated at the negative electrode completely reduces the lead oxide to **metallic lead**, while on the other hand the positive electrode becomes oxidised as far as possible, to **peroxide of lead**, or PbO_2. When the charging current ceases, the **peroxide of lead** acts like the **copper** in an ordinary cell, and the **clean lead** plate acts like the **zinc**: a discharging current passes round the circuit from the PbO_2 to the Pb in the connecting wire, and from the Pb to the PbO_2 in the dilute sulphuric acid. At the same time the PbO_2 and the Pb are respectively reduced and oxidised to PbO which, in the presence of the sulphuric acid, becomes $PbSO_4$ on both plates. When a charging current is again sent through, this again becomes PbO_2, free sulphuric acid, and Pb respectively. Such a Storage or Secondary Cell is very useful, for it may be connected with an ordinary Galvanic Cell or battery as in Fig. 276; then if the charging current be not too strong, it will go on charging the secondary cell until the continually increasing tendency to a back-current through the charging battery becomes equal to the tendency of the charging battery to pass a current through the secondary cell; at which period, and whereafter, there is equilibrium. If the current be stronger than is necessary for this, the storage battery when fully charged goes on **bubbling** or "boiling" by mere ordinary **electrolysis**. In the arrangement of Fig. 276, the tendency of the secondary cell is to **reduce** the current until it has itself become **fully charged**, but after that it **does not interfere** with the main current. On the other hand, if the battery CuZn flag or be withdrawn, the secondary cell will go on producing a current **in the original direction** round the working circuit. Such a cell or a battery of such cells therefore serves as a **steadier** of the current coming from a source (such as a dynamo) the flow from which is not quite steady; and in that way a Secondary Cell or Battery plays a part analogous to that of a

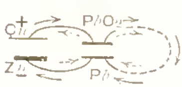

Fig. 276.

fly-wheel in mechanism. Further, when such a storage cell or battery is charged, it can be **carried about** with its circuit open; and then, whenever its circuit is closed, it will give a current which may be utilised for the incandescence of an electric lamp or an electric cautery or knife or cautery-wire. A secondary cell should never be fully discharged; and it cannot be overcharged, for if the attempt be made to overcharge it, it "boils," evolving electrolytic oxygen and hydrogen. If a cell be discharged, its voltage should not be allowed to fall below 1·90 Volts, and then its Efficiency will be from 65 to 70 per cent: that is, from 65 to 70 per cent of the Energy of charge will be recovered; but it is not safe to allow the rate of discharge to exceed about one Ampère per square decimetre of plates, for there is a tendency, if there be too little Resistance in circuit, for the plates to break up and crumble. With these precautions, a lithanode battery (compressed peroxide of lead) will give out, after being charged, about 5 Ampère-hours per lb. of material, at from $2\frac{1}{2}$ down to 2·1 Volts per cell.

If we try to find the **resistance** of a **galvanic cell** or an **electrolysable liquid** or of the **human body** by the means suitable for ordinary conductors we fall into confusion; for Polarisation complicates the results. If however we put a known Resistance in AB (Fig. 247), and the unknown in BC; and a Telephone, not a galvanometer, at G: and if we connect with A a single wire leading from the secondary coil of an ordinary medical induction-coil; then, if we slide the wire at D back-and-fore until there is no sound heard in the telephone, the ratio of Resistances given at Fig. 247 then applies. The angle C has nothing connected with it.

Arrangement of Galvanic Cells.—When we have a number of cells of any kind at our command, we may in the use of them have either of two objects in view: to work them as **economically** as possible, or to get the greatest possible **current-strength** or Ampèreage.

In order to work them as economically as possible we must **keep down** the Resistance of the battery. This is effected by joining all the cells "**in surface**," all the zincs to one another and all the coppers to one another.

Suppose we have an external Resistance of 10 Ohms, and that we have at disposal say 60 Grove cells, in each of which the resistance is 0·6 Ohm and the Voltage say 1·8 Volts. Joining all the platinums together and all the zincs to one another, we form a virtual single cell of sixty-fold surface: and the Resistance of this is one-sixtieth of the resistance of a single cell; that is, it is 0·01 Ohm. But nothing has happened to alter the voltage, which remains at 1·8 Volt, just as if a single Grove cell had simply been fitted up, of enormous size. The Current produced by this arrangement is, in Ampères, equal to Volts ÷ Ohms. The Volts are 1·8 simply; because the cells act virtually as one large cell. The Ohms are 0·01 internal and 10 external, = 10·01. The Current is therefore $\frac{1·8}{10·01}$ = 0·1798 Ampère. The total Energy transformed in the circuit (= (Ampères)^2 × Ohms) = (0·1798)^2 × 10·01 = 3·2367 Joules per second; whereof $\frac{0·01}{10·01}$, an insignificant proportion, is wasted by transformation into Heat in the battery itself. The current produced is small for such a battery, but such as it is, it is nearly all applied in the circuit, while hardly any is wasted in the battery itself.

To get the greatest possible Strength of Current we should so arrange our cells as to make the internal **resistance** of the **whole battery** as nearly as possible **equal** to the **resistance** of the **working circuit**, from terminal to terminal.

When cells are arranged tandem-fashion, in Indian file, or "**in series**," the zinc of each cell being connected with the copper of the next, the Resistance of the battery is, if there are n cells, equal to n times the resistance of a single cell, for the same current has to traverse all the cells in succession.

When we have ab cells (say 60 cells) arranged in a **groups** (say 12 groups) of b cells each (say of 5 cells each), with the b cells of each group arranged in surface and the a groups connected in series, the Resistance of the battery is a/b times that of a single cell. The possible groupings of 60 cells would be $a = 60$, $b = 1$ (arrangement in Series); $a = 30$, $b = 2$; 20, 3; 15, 4; 12, 5; 10, 6; 6, 10; 5, 12; 4, 15; 3, 20; 2, 30; and 1, 60 (arrangement in Surface). The relative Resistances are 60/1 = 60; 30/2 = 15; 20/3 = 6$\frac{2}{3}$; 15/4 = 3$\frac{3}{4}$; 12/5 = 2$\frac{2}{5}$; 10/6 = 1$\frac{2}{3}$; 6/10 = $\frac{3}{5}$; $\frac{5}{12}$; $\frac{4}{15}$; $\frac{3}{20}$; $\frac{1}{15}$; and $\frac{1}{60}$ times the resistance of a single cell. With cells of 0·6 Ohm resistance each, the Resistances of the whole Battery, in Ohms, would be 36, 9, 4, 2$\frac{1}{4}$, 1·44, 1·0, 0·36, 0·25, 0·16, 0·09, 0·04, and 0·01. Of these the **nearest** to our **external resistance** of 10 Ohms is the *second*; 30 groups of two cells each, the groups in series and the two cells in each group arranged in surface.

Then what is the **current** produced by this arrangement? The Ampères = Volts ÷ Ohms. The Volts are 54; because all the 30 groups in series back one another up; and 30 × 1·8 = 54. The Ohms are 19; 10 external and 9 internal. Therefore the

Ampères are $\frac{54}{19} = 2{\cdot}84$. The total **energy** transformed in the circuit, per second, is equal to $(\text{Ampères})^2 \times \text{Ohms} = (2{\cdot}84)^2 \times 19 = 153{\cdot}46$ Joules per second; and of this $\frac{9}{19}$ is wasted in the battery, by transformation into Heat.

If the External Resistance be **greater** than that which can be offered by the battery even though all its cells be grouped in **series**, the best we can do is to group all our cells in series. If with our battery of 60 cells, of 0·6 Ohm resistance each, we had to send a current through a resistance of 100 Ohms, we would arrange all our cells in Series, thereby making the resistance of the battery equal to 36 Ohms; and the data would be, Volts 108 $(= 60 \times 1{\cdot}8)$; Ohms $36 + 100 = 136$; Ampères $\frac{108}{136} = 0{\cdot}794$; Energy $(0{\cdot}794)^2 \times 136 = 63{\cdot}062$ Joules per second, whereof $\frac{36}{136}$ is wasted as Heat in the battery.

We may want to send a **determinate current** through a given Resistance. For example we may want to send an actual steady current of 30 milliampères ($\frac{30}{1000}$ Ampère) through some part of the human body, say the arm. We may have an idea that the resistance of the arm is likely to be greater than the internal resistance of our battery, even when all our cells are arranged in series; and accordingly, on the lines of what has just been said, we may determine to put all our cells in **series**. If our apparatus be such as will enable us to switch **each cell independently** into the circuit, we ought not to begin with the full battery power, for we might by chance do mischief: we should put cells **successively** in circuit, in **series** with one another, until we obtain the strength of current required, as shown by our milliammeter. If we do not get the required current with the whole of the cells in series, we shall not get it at all with our battery, which is insufficient for the purpose. If we get it before we have introduced all our cells into circuit, we let matters rest as they are, for with a large external resistance the arrangement in series is already the most economical, and the limited number of cells in series has proved itself sufficient.

Another method would be to adjust the current as a preliminary, through a **resistance-box** having a resistance somewhat greater than the expected value of the resistance of the arm. When the current through the resistance-box is the required $\frac{30}{1000}$ Ampère, put the arm in the circuit, so that the current goes through **both arm and resistance-box**. By this the current will be materially reduced: but the resistances in the resistance-box may be gradually **removed** by operating successive plugs until the current again comes to its adjusted value. The plugs which have been put in or taken out, as the case may be, then indicate the total Resistance of the arm introduced into the circuit, which does not remain constant. Care would naturally be taken not to begin by throwing too large a resistance-coil out of circuit at first; it will be well to work up to the desired current-strength more tentatively, and to replace successive groups of smaller coils each by one larger one.

It may be noted that as a matter of course, wherever instead of keeping down the power of the battery itself we put **resistances** into a circuit in order to moderate the strength of the current, there is a **waste of energy** through production of **heat** in the resistances so put into the circuit, and a corresponding waste of zinc in the battery. This is manifest when an electric **incandescent lamp** is used as a Resistance; the Light and Heat produced are generated at the expense of the Energy of the electric current.

IV. **Thermoelectric methods.**—Let bismuth, Bi, and antimony, Sb, be connected (Fig. 277) at the two junctions H and C. Let one of these two junctions, H, be heated; let the other, C, remain cool; a current will pass round the circuit, BiHSbCBi, in the direction **bismuth to antimony** across the **hotter** junction H. This current is very feeble, but the effect may be multiplied by increasing the number of hotter and cooler junctions in the circuit, after the fashion of Fig. 278.

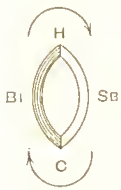

Fig. 277.

The slightest difference between the temperature of HHHH and that of CCC causes a very small current to pass. But since it is very easy to detect very small currents, it is very easy to detect very **small differences** between the **temperatures** of HHHH and CCC.

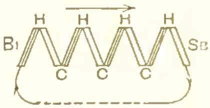

Fig. 278.

This principle is applied in the Thermoelectric Pile or **Thermopile**, in which the alternating junctions HH are very numerous and are gathered together into a facetted face which is exposed, say, to radiation, or to direct heating from any particular source. The circuit is completed round a delicate galvanometer, or through any other current-measuring contrivance.

Another application of the principle of the Thermopile is the **thermoelectric thermometer** sketched in Fig. 279, and used, for example, for finding the temperature of the subsoil at different points. The two wires WW connect two bismuth-antimony junctions C and H: if these be at the same temperature, there is no current in the circuit. If, however, the junction H become warmer than C, a current runs in the direction BiHSb, and round the galvanometer G. The temperature of H may be ascertained either from the readings of the galvanometer, with the aid of a calculated or observed table of corresponding temperature-differences, kept for reference: or else by altering the temperature of C until the instrument G indicates no current; C and H are then at the same temperature. Then the temperature of C may readily be ascertained by means of a thermometer, and therefore that of H is also ascertained. In thermoelectric needles we have the principle of the Thermoelectric Thermometer applied to apparatus which may be used to explore the temperatures of the human body. Thermoelectric thermometers are far more sensitive to small differences of temperature than mercury thermometers are. They can indicate the rise of temperature which occurs when the brain is active.

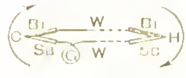

Fig. 279.

Thermoelectric Piles are also used as sources of current, though not much so; but where they are used they are very convenient, for they require no preparation beyond lighting the gas, which, by bunsen-burner flames, keeps the junctions HHHH hot. In Gülcher's thermopiles, the metallic junctions H and C are between tubes of argentan (a nickel alloy) and hollow cylinders of a hard antimony alloy: the Resistance, with 66 elements, is from 0·5 to 0·65 Ohm, the Voltage is 4 Volts, and the Ampères consequently about 6·4 as a maximum; the consumpt of gas is about 170 litres (6 cubic feet) per hour; and the Efficiency, that is, the proportion of the energy of combustion of the gas which is converted into the energy of electric current, is about 1·04 per cent as a maximum. In other forms of thermoelectric pile, the maximum efficiency does not usually exceed 0·35 per cent. Considered as a form of apparatus for conversion of one form of Energy into another, the thermopile is therefore very wasteful; but it is cleanly and convenient, and its waste is that of a sufficiently cheap form of fuel, while the flame can be turned on and off without any trouble.

V. **Energy of Rotation.**—The means by which Differences of Potential are produced by **dynamo-electric machines** or "dynamos" will be described later on (p. 458).

Other Methods.—The other methods of producing differences of potential may be briefly discussed, since they are of comparatively small practical use.

VI. When a **jet** of partly-condensed **steam** or of suddenly-expanding undried air is driven through a conical nozzle of metal or glass or wood, the stream of air becomes positively, the vessel from which it is driven becomes negatively charged. If the nozzle be of ivory there is no charge. If the vessel contain some turpentine oil, the charges are reversed. These facts were discovered by accident at Messrs. Armstrong's works at Newcastle, and very powerful electric machines have been made to replace the frictional machines used for high-tension discharges. A liquid in the spheroidal state (see p. 127) is generally found to be electrified.

VII. In the tranquil **evaporation of water**, there does not seem to be any electrification set up; but if there be any **friction** of the vapour against the liquid or, in the case of solutions, if there be any friction of the crystals upon the vessel or upon the hot solution, or any crackling of the crystals, there will be a difference of electric condition between the vapour and the liquid evaporated. If such a difference be set up in the evaporation of water, the steam is generally positively charged.

VIII. When **pressure** or **traction** is applied to **tourmaline** crystals along the crystallographic axis they become differently charged at the opposite ends of this axis.

IX. Similar results follow when such crystals are **heated** or **cooled**.

X. When **mercury oscillates** under water in a **conical tube**, so that its upper surface goes on changing in its area, the electric condition of that surface between the mercury and the water undergoes corresponding alterations, and there are differences of potential or altered differences of potential set up between the mercury and the water. This principle is applied in a form of **microphone** due to Lippmann, in which vibrations of a membrane A cause corresponding vibrations of the surface of the mercury at B: above B lies acidulated water. Into the mercury and the acid respectively there are wires inserted which form part of an electric circuit; and in that circuit a current runs, which fluctuates in strength in accordance with the vibrations of the membrane A.

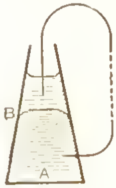

Fig. 280.

XI. **Flames** may sometimes be used as means of producing differences of potential, as in the case of a gas-flame which gives the surrounding air a negative charge, while the combustion of glowing carbon gives it a positive charge.

XII. Electric currents are also found to exist, naturally, in living **nerves** and **muscles**. They are weakened during contraction of the muscle or the active state of the nerve. Becquerel found that an alkaline and an acid fluid, separated by an animal membrane, developed a current which ran, in a connecting wire, from the alkali to the acid. He was inclined to attribute the natural currents of nerves and muscles to this.

XIII. Some **animals** have distinct electricity-generating organs. The **electric torpedo (Raja torpedo)** has a four-lobed apparatus equivalent to a battery of 2000 plates. The dorsal region of the fish is positive, the ventral negative: and the fish can, if irritated, keep an electric incandescent lamp aglow. The evolution of Energy in this form is said to cool the fish itself distinctly.

The Variable Period

The various phenomena of Electric Current of which we have hitherto spoken are those of a current when it has once been fairly set up and is in a **steady** or uniform condition. We have now to mention certain phenomena of the period during which a current is **being set up**, or being **varied** in its strength from one value to another.

This period, which is called the **Variable Period**, is a period of **adjustment** throughout the whole Magnetic **field**; and during this period **the** Ether in the Field seems to be gathering up or giving out **Energy**. When a current is being set up, there is a certain **retardation** or holding-back of the current, which does not at once reach the distant end of the circuit in full strength, but takes some time to attain a given proportion of its full ultimate value. For this reason signals on a long line, such as the Atlantic cable, take some time in reaching the other end; not that any appreciable time is taken in producing **some** effect at the other end, but that the current remains too small to be perceived by any but a most delicate instrument at the distant station; and the more delicate the recording instruments, the more rapidly may the arrival of the signal-currents be detected and the signals read off. When the current is suddenly **stopped** at the home end after having attained a Steady State, the **cessation** of the current at the distant end is again deliberate and **retarded.**

During the Variable Period the Field is, as has been said, in a state of adjustment. One result of this is, that if **in the field** there be **any wire** in which a current can flow, in that wire a **current** will flow, so long as the **variable state** of the Field endures, but no longer. The field may be brought into this disturbed state by two methods, which are, after all, essentially the same, namely, (1) the production of a new **current** or the cessation or diminution of an existing current, or (2) the approach or strengthening or the recession or weakening of a **magnet.**

Both these methods involve in reality only one alternative, that is, the **strengthening** or **weakening** of the surrounding Magnetic Field. The **direction** of the Current which is **induced** in a wire in the field is such in both cases as to satisfy only **one criterion**, namely, that the existence of the new Current tends to **prevent the change** which is going on in the condition of the Field.

Let the student look at any ordinary **medical induction coil.** He will there find that a bobbin, wound round with a coil of insulated wire, is slipped over another bobbin also wound round with insulated wire, and that this inner bobbin may or may not have, but usually has, a soft iron core, generally of soft iron wire. Now let a **current** be passed through the **inner coil,** and be kept **steady** by tying the oscillating hammer up so that it cannot approach the soft iron core; then the Magnetic Field in the interior of the inner coil acquires a certain strength; but should the current increase, then the interior field will become stronger. Nextly, if we may imagine that while the inner current had been increasing, and the interior field accordingly becoming stronger, there had been at the same time an **opposite** current developed by any means in the **outer coil**, the effect of that outer current would have been to weaken the interior field, and thus to neutralise, or tend to neutralise, the field-strengthening effect of the increase of current in the inner coil. This is exactly what happens. There is spontaneously developed in the outer coil, during the period of increase of the current in the inner coil, and **no longer**, a current whose direction is **opposed** to that of the **increasing current** in the inner coil; and this induced current tends to thwart the field-strengthening effect of the increasing primary current.

On the other hand, if the **current** in the **inner coil fall off**, there is again a Current in the outer coil, which is on this occasion in the **same direction** as the waning current in the inner coil; and this induced current in the outer coil again lasts only during the period of the waning of the primary current. Currents so induced in the outer coil are called **Secondary Currents**, in relation to the waxing or waning current in the inner coil, which is, in relation to them, called the **Primary Current**; and correspondingly, the inner coil is called the **primary coil** and the outer one the **secondary coil**.

From this we may understand that even in the simplest case, that of **two circuits** laid **side by side**, as in Fig. 281, when a current is abruptly **made** in the primary circuit P by pressing down the key K so as to make contact there and close the circuit, a Secondary Current of extremely brief duration and **opposed** in direction is formed in the secondary circuit S; and if we look only at the parts of the respective wires which lie alongside one another in the neighbourhood of the arrows in the figure, we may say that the setting up of a current in one wire is accompanied by a very brief current in an opposite direction in another wire laid alongside the former. When the current wanes or is abruptly **stopped**,

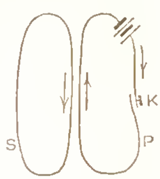

Fig. 281.

there is again a Secondary Current, this time in the **same direction** as the waning or broken current.

It is to be remarked that the Secondary Current is limited in respect of its **duration** ; a certain quantity of Electricity has to flow, which is determined by the relative proportions and position of the two circuits : and if the Secondary Coil be one of **high resistance** and many turns, the **voltage** of the secondary coil will be **high**, so as to get the current through in the time. Therefore if a secondary circuit, in which there is a secondary coil whose turns of wire are numerous in comparison with those of the primary coil, be broken by an air-gap, **sparks** may leap across that air-gap, across a distance which the primary current could not have leaped over ; and further, as the **break** or stoppage of a current is **more abrupt** than its establishment upon the closure of the circuit, the secondary circuit may present **sparks** across such a gap at the **break** of the primary current, even when the same circuit does not present any such sparks at the making of that current.

A magnet swung in a copper box soon comes to rest ; by its motion it produces **induced currents in the copper** ; and these induced currents are such as to offer Resistance to the motion which gives rise to them. By this means the oscillations of a galvanometer-needle may be checked or damped, so that the instrument becomes **aperiodic** or "dead-beat."

In the "**Induction coil**," the **primary** coil, the **inner** one, is made of a **few turns** of **thick** insulated wire ; the **secondary**, the outer one, is made of **many turns** of **thin** insulated wire. Each coil has its own pair of terminal binding screws ; the primary is connected with the battery (say a single bichromate cell) and with some contrivance for making and breaking the circuit ; the secondary is connected with whatever we may wish to pass the secondary currents through. When the primary current is made, there is an abrupt current of high voltage in the secondary circuit ; when it is broken there is another current, in the opposite direction (that is, in the same direction as the broken primary current), still more abrupt and of still higher voltage.

Instead of using a key to make and break the current in the primary circuit, we may use a "**contact-breaker**" to make and break the current with great frequency. This may be a **mechanical** contrivance, such as a cog-wheel with teeth pressed upon by a metal spring, interpolated in the primary circuit and rotated by hand; or it may be automatic, as in **Neef's Hammer.** In this the soft-iron core within the primary bobbin, becoming powerfully magnetic when the current passes, attracts a piece of soft iron poised near its end, which piece of soft iron forms an integral part of the primary circuit; this piece of soft iron moves towards the soft-iron core; but in so doing, the movable piece of soft iron moves away from a metallic screw, contact with which is necessary to the continuity of the primary circuit. The continuity of the primary circuit is thus broken, and the primary current suddenly stops.

If the contact be made and broken **in vacuo**, the action is very abrupt. If the contact be made and broken by lifting a wire up and down at the surface of mercury, it is advisable to cover the mercury with water, in order to prevent sparks.

When the primary current ceases on being thus broken, the soft-iron core loses its magnetic properties; it then ceases to attract the soft-iron mass; this soft-iron mass is fetched back to its original position by a spring; and then the continuity of the circuit is restored, again to be broken in consequence of the action of the current itself as before. This cycle is repeated with great frequency, which may be modified by adjusting the distance which the soft-iron mass or armature has to travel back-and-fore, or by adjusting the tension of the spring which tends to keep it pressed against the contact-screw.

In the Secondary Coil we then have an alternating succession of abrupt currents of high voltage, in opposite directions; and a rapid succession of alternating abrupt or intermittent currents of this kind is called, in medical work, a **Faradic current**, as distinguished from a steady or Galvanic current.

The Strength of the induced Faradic Current may be **regulated** by sliding the secondary coil more or less completely over the primary.

If the construction of the instrument be reversed, that is, if the primary coil, still inside, be one of many turns and the outer secondary coil be of few turns, the secondary currents are of **lower voltage** and greater Strength than the primary; and this is the principle of the **Transformer** used in electric lighting work. In the use of transformers, the primary currents employed are not abruptly made and broken, but **oscillate** back-and-fore, their variations of current-strength corresponding very closely to the **vibrations of a string**. Such currents may accordingly be said to present nothing but the Variable Period, and as they oscillate back-and-fore, a Secondary Current, of lower voltage and greater quantity, oscillates fore-and-back in the secondary coil. Oscillating currents of excessive Voltage, supplied from "alternating current" electric mains, are thus "transformed" into oscillating currents of more manageable and safer voltage, for use within dwellings and other buildings.

A Primary Circuit may even act to some extent as its own Secondary Circuit. This phenomenon is known as **Self-Induction.** If we try to pass a current abruptly through a coil (for example the primary coil of an induction coil), the different turns act on one another, and **each turn** of the coil tends to induce an **opposed current** in the other turns, during the Variable Period. The result of this is a certain Resistance to the setting up of a current in a coil. Conversely, when the current is broken, there is a corresponding resistance to its stoppage, so that the current, as it were, plunges on and piles up an electric charge at the extremities of the wire; and if the coil be large enough, there may thus be produced a high Voltage, with corresponding **sparking**, at the ends of the broken wire. There is no case in which this phenomenon of Self-Induction is entirely absent, even in a single-loop circuit; but practically we must, in order to encounter it, have either a **very large** simple circuit, such as a deep-sea cable line, or a circuit containing a **coil** of many turns.

In Von Helmholtz's arrangement of Neef's hammer, for physiological purposes, the current is never completely cut off, so that the effect of self-induction is minimised, and the shock at the break is the same as that at the make.

Dynamo-Electric Machines.—We have already said that when a Magnetic Field is strengthened or weakened, a coil in that field has a Current induced in it. But there may be cases in which while the Field itself remains unchanged, it may in effect be rendered weaker or stronger **relatively to the coil.** Take three positions of the coil in the field. In Fig. 282 A the coil stands facing all the field lines, or Lines of Magnetic Force, end on, and the greatest possible number of these pass through it: relatively to the coil, therefore, the Field is then at its **strongest.** In Fig. 282 B, the number of lines which traverse the coil is smaller than in Fig. 282 A, and relatively to the coil the Field is **weaker.** Next take the position of Fig. 282 C. There the coil is at right angles to its former position and no field lines pass through it at all; relatively to the coil, the Magnetic Field is then as though it were not. Now let us make the **coil rotate,** round its own diameter, from position A through position B to position C. During this movement the Field is gradually **weakening** relatively to the coil; and during that period an induced **current** passes in the **wire** of the coil. Next, will the current be **uniform, or not,** during the quarter-revolution shown? We can see that in the position A, an exceedingly small displacement produces no effect upon the Number of Lines which pass through the contour of the coil. Therefore, if the coil be subject to continuous rotation, there is **no current** at the instant when the coil is passing through **position A.** When, on the other hand, it is passing through **position C,** the change in the Number of Lines is the most rapid possible: the Lines of Force are then being **cut** (and left outside the coil) not obliquely but directly **across.** When the coil is passing through the position C, the induced **current** is therefore a **maximum.** If the course of events be followed during the next quarter-revolution, it will be found that the current still continues in the same direction round the loop but with **waning** current-strength, until the coil assumes a position the same as that of A in Fig. 282, but with this difference, that the back of the coil is now where its face had been. When this angular position is reached, the **current** has fallen back

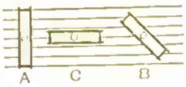

Fig. 282.

to **zero**. In the half-revolution, then, the current-strength has risen from Zero to a Maximum and fallen back to Zero. We may represent this, if the rotation be uniform, by a diagram, Fig. 283. This curve, when worked out in detail, is of exactly the same form as the **harmonic curve** which indicates the successive displacements of any given point of a vibrating string during one half-oscillation.

Fig. 283.

During the next half-revolution, the result is precisely similar, with the exception that the **back of the loop** now takes the place of its former front. The induced current now runs round the back of the coil in the same direction as it had run round its front in the first half-revolution, waxing and waning in the same way. It will be seen on taking a coin in the hand and passing the finger round its rim in a given direction; and then turning the coin face-over and again passing the finger round the rim in the same direction; that the movement of the finger in the latter case is really, as regards the rim of the coin, opposite in its direction to the movement of the finger in the former case. In a similar way, the **two current-directions** during the two half-revolutions, which are **the same** in relation to the Field, are in reality **opposed** in reference to the Coil considered alone, because between the two half-revolutions the coil has reversed the aspect presented by it to the field. Along any given bit of the wire of the coil, then, the current is, starting from the position A, first in one direction waxing and waning, then passing through a zero value, and then waxing and waning but in an opposite direction. The whole cycle of variation of current-strength may be represented by the diagram, Fig. 284, which is the same as one complete wave-length of a **harmonic curve.** Each complete cycle is called one Alternation.


Fig. 284.

The coil, as we have seen, rotates on an axle: and we may bring out the ends of the wires to metal rings fitted on the axle. While the coil is rotating on its axle, let us touch these two rings with the two ends of a metal wire; then that wire will form, along with the rotating coil, a **complete circuit**. In that circuit a Current will pass, which current will oscillate or **alternate** in its direction of flow, waxing and waning at each half-alternation, after the fashion of Fig. 284. One complete **alternation** corresponds to **each revolution** of the coil: and the more rapidly the coil is rotated, the more rapidly will the alternations follow one another.

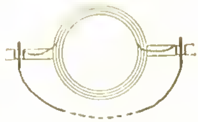

Fig. 285.

There are numerous possible variations in the application of this principle. For example, the coil may not rotate round its own diameter, but round some other axis of rotation parallel to that diameter; the consequences are similar, one complete alternation, that is one positive and one negative flow of current, to each complete revolution.

Again, we may not desire to have our resultant current an alternating one: in which case we use a **Commutator**, instead of the plain rings of Fig. 285. A Commutator in its simplest form (Fig. 286) is made of two half-rings ranged opposite to one another and mounted on a wooden or otherwise isolating portion of the axle. One of these plates is permanently connected with the one, and the other with the other end of the coil-wire. The external circuit has its free ends (flat flexible plates or "**brushes**") so arranged as each to touch one of these half-rings: and as the axle rotates, at the instant the direction of the current changes in the coil, the brushes exchange the half-rings upon which they rest, so that the Direction of the Current **in the external circuit** remains always **the same**. But the current in the external circuit **fluctuates** in strength: it varies after the fashion shown in Fig. 287. Therefore a simple coil with a simple commutator is not a satisfactory contrivance for practical purposes in the production of a direct current. Great ingenuity has accordingly been expended in the development

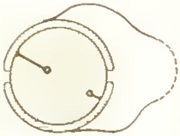

Fig. 286.

Fig. 287.

of the modern dynamo machine, in which **many loops** or turns or coils of wire are aggregated into a rotating congeries called the **Armature**: but the action of **each** several **turn** of the wire in the Armature is in principle the same as that of the simple loop just described: and by means of a more complex commutator the different loops or coils, or groups of these, in the armature are made to deliver their several currents to the external circuit in such a way that these **overlap** one another and thus get rid, approximately, of the fluctuations of current-strength. It will be obvious, therefore, that the armature of a dynamo has to be differently designed according as it is intended to be used for producing Alternating Currents or for having these commutated into a Direct Current; and that it will have to be differently constructed according to the Voltage and Ampèreage which will be required as the output of the machine.

We have assumed in the above that a Magnetic Field exists for the loop or coil to rotate in, and that this magnetic field is **uniform**. If it be not uniform, the current-strength does not vary precisely after the fashion of a vibrating string; but the curve still bears a general though distorted resemblance to the harmonic curve.

In the earliest machines actuated by the rotation of coils within Magnetic Fields, **permanent steel magnets** were used to produce the required field.

The permanent steel magnet survives in the **medical magneto-electric machine.** In this the required weakening or strengthening of the Field, relatively to the coil, is accomplished not by rotating the coil round a fixed axis in the way just described, but by bodily moving bobbins, bearing coils, from stronger to weaker parts of the field and *vice versâ*. These bobbins, a pair of them, are made to rotate so as to **flash past the poles** of a permanent steel magnet, and are thus pulled in and out of the strongest parts of the field: currents are thus formed in them, which may or may not be directed by a Commutator so as to make them travel in the same direction. The Strength of the Field itself may be **regulated** in the way already described (p. 415), by an adjustable bar of soft iron.

Then again, the required Magnetic Field was, in many forms of machine of this kind, that between the Poles of soft-iron **electromagnets** excited by a **separate current** from an independent machine or battery. But the great stride in advance which rendered these machines practical was the discovery of the "**dynamo-electric principle.**" This is, that the **current** from the **machine itself** may be made to excite the **electromagnets**, and thus to keep up the required Magnetic Field.

The starting-point is, that if the electromagnets be not of too soft a sample of iron, they always retain a **trace** of magnetic condition, even when the exciting current ceases. There is therefore a Magnetic Field. True it is an **exceedingly feeble** one, but it generates a certain very **feeble current** when the machine is set to work. If the current produced be led **round the electromagnets**, this current strengthens the electromagnets: these in their turn give rise to a stronger Magnetic Field and to the induction of a more powerful Current: and this train of action and reaction is repeated until the strengths of the electromagnets, of the magnetic fields, and of the induced currents attain the **maximum** possible under the existing conditions. Various modifications of this principle have been adopted, such as sending a part only of the current round the electromagnets, sending a part at all times and the whole of the current only when the external circuit is active, adjusting the relation of the parts of the current so sent, and so forth: but these are details which we now pass over.

Some dynamos which deliver alternating currents are driven at extreme speed: others use a device analogous to that of the medical magneto-electric machine, and flash a series of coils past a number of alternately positive and negative electromagnet poles ranged in a circle.

Electromotors.—When a Dynamo Machine is **reversed** in its action, that is when a Current is sent through a dynamo instead of its sending out a current, the dynamo tends to **rotate backwards**, and to transform the Energy of a Current sent through it into the Energy of Rotation; but this would make it run against its brushes. If, however, the brushes be set backwards, any ordinary dynamo will serve as a more or less efficient Electromotor, driven by the current supplied to it. When an electromotor is put into the circuit of a dynamo, and allowed to run, it may be that the **actual current** perceptible along the two wires which connect the dynamo with the motor is greatly **reduced**; for the

motor itself acts, when running, as a dynamo, and it produces a backward or **Reverse Current** which tends to neutralise the original current of the dynamo.

By Electromotors an extreme speed of rotation can be produced, as for instance in **dentists'** apparatus and in the **hypnotic fascinator**.

The law for the Transmission of Energy by direct currents is the same as that for the production of Heat in a conductor, namely: Joules per second = the Ampères × the Volts consumed in the motor: and it will be remembered that one Joule per second corresponds to an Activity of $\frac{1}{746}$ horse-power: so that a current of 5 Ampères, if the terminals of the running motor are at potentials differing by 200 Volts, corresponds to an absorption of Energy in the motor of 1000 Joules per second, or a Transmission of Energy from the driving dynamo at the rate of $\frac{1000}{746}$ horse-power.

Alternating Currents

The successive alternations of the induced current delivered by an alternating-current dynamo follow one another with a **frequency** ranging from about 40 to about 150 per second. This order of frequency is very different from that of the oscillations in a Leyden jar discharge, which run from say 1 to 10 millions per second or more: but even with the currents from an alternating-current dynamo, there are certain peculiarities to be observed which are common to **alternating currents** of all except the lowest frequencies. The higher the rate of alternation, the more does the current tend to be confined merely to the **outer skin** of the conducting wire, that is to say to the Electric Field, the Ether itself; and hence **tubes** convey such currents as well as rods do.

It has long been considered in medical practice that Faradic currents were much more superficial in their action than continuous currents.

The Apparent Resistance of a wire to an Alternating Current is therefore something very different from its

Resistance to a Steady Current; and it tends, as the frequency increases, to acquire a value proportional not inversely to the cross-section of the wire, but inversely proportional to its **circumference**. This resistance is called the **Impedance** of the conductor; and it is not constant like the Resistance, but varies according to the way the wire is coiled up, and according to the frequency of the alternations.

Alternating currents produce **Heat**, which is proportional to the *average* value of the *square* of their Current Strength; and they can produce **Light**, as in arc and incandescent electric lamps: but in arc-lighting they have a tendency to produce noise in the lamp. Being not properly directed to that effect, they can **not** produce any **electrolytic** effect, because what they do at one half-alternation, they undo at the next.

A coil through which an alternating current is passed acts in a non-uniform magnetic field not like a magnet, but like a **Diamagnet**; it is repelled into the weakest part of the field, and tends to lie across the field-lines.

When an alternating current is passed into a coil of many turns, there is a tendency for it to **choke down** so that no current passes; for the Impedance, or apparent resistance, then becomes very great.

If an object be **hung by one wire** upon a wire bearing an alternating-current, that object becomes, with corresponding rapidity, **alternately** positively and negatively electrostatically **charged**: and this may result in such a shattering of the outer molecules of the object itself, and of the adjacent particles of the air, that the surface of the object and the air around it become **heated** or may **glow brightly**. This effect is very easily produced with the air remaining within a Geissler-tube; and if a Geissler-tube be held in one hand while the other hand is connected with one of the terminals of the secondary coil of an Induction Coil (in which the **primary current** is itself subjected to **alternations** of **extreme frequency**, as where a Leyden-jar is put in the circuit of that primary current and is made to discharge itself continuously), the Geissler-tube **glows in the hand**. The charging and opposite charging of the Geissler-tube must be effected through the human body, and **alternating currents** must run **through the body** with extreme Frequency under an enormous Voltage; yet no harm is done; no more than by the impact of Light, which appears to be an entirely analogous phenomenon, one of extremely rapid alternations of electric condition in the Ether. Experiments of this order are numerous and varied, and are due to Mr. Nicola Tesla.

In the **Telephone** audible sounds, the Human Voice, etc., are reproduced at a distance by means of electricity. The Sound to be reproduced has its mechanical equivalent in the **air-waves** which give rise to the sensation of sound. These air-waves are **complex-harmonic** vibrations of the air, and they will exert a correspondingly varying Pressure upon any membrane or disc exposed to them. In the simplest form of Telephone, to which we confine our attention, they are caused to impinge upon, and thus to exert varying pressure upon a **soft-iron disc** A.

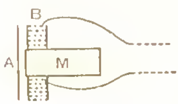

Fig. 288.

This disc yields more or less to the **fluctuating pressure.** In some cases this disc is only the central part of a more yielding membrane. The next part of the apparatus is simply a coil-bearing bobbin B, with a magnet M serving it as a core. The complex-harmonic movement of the soft-iron disc A in the neighbourhood of the magnet M causes a corresponding disturbance of the Magnetic Field of M; and the consequence of this is a corresponding complex-harmonically **alternating induced current** in the wire wound round the bobbin B. The original variations in the air-pressure on the soft-iron disc are thus reproduced in the Oscillations of Electric Current in the bobbin. The wires of the bobbin are connected by long-distance wires with a similar instrument at the receiving station. The oscillating currents, as received at the receiving station by the bobbin B′, cause **variations** in the Strength of the **magnetic field** of the **second magnet** M′. These variations cause corresponding variations in the Force with which the receiving soft-iron disc A′ is pulled upon.

The receiving soft-iron disc yields to these varying forces in an oscillating manner, and causes oscillatory **variations** in the **pressure** of the **air** at the surface of the disc. These variations are propagated through the air to the listening Ear, and the original sound is heard reproduced.

Not perfectly, however. Apart altogether from the distortions in the oscillating signals caused by so many transmissions from one part of the apparatus to another, there are distortions of the signals caused by the nature of alternating currents and their peculiarities of transmission along wires. The higher components, those of greater frequency, are not transmitted at the same speed as the lower components, and they tend to thin away and wear out more rapidly than the lower ones; so that the quality of the sound, as transmitted, is changed.

In the **microphone**, a Steady Current is made to pass through a **carbon** rod **supported loosely** between two hollowed-out carbon blocks, or through a quantity of loose carbon dust: **vibration** causes variations in the **contacts** through which the current can be conveyed and a corresponding variation in the **conductance** of the circuit. A Steady Current is thereby made a slightly **varying current**, and its variations will be detected by the receiving Telephone.

A microphone mounted on a stethoscope may be made to record **heart-sounds**, through generating a current which acts upon a muscle-nerve preparation.

In the **photophone** a **mirror**, itself **flexible**, reflects light to a distant point: the back of the mirror is spoken at; it vibrates, and the **light** reflected to the distant point undergoes corresponding **fluctuations** in brightness as the mirror becomes flatter or more concave. At the distant point the light, thus varying, falls upon crystalline **selenium**. Curiously, the **conductivity** of selenium **varies** in accordance with the brightness of the Light falling upon it. This selenium forms part of a circuit in which a current runs, and in which a Telephone is inserted. As in the case of the Microphone, the variations of conductance of the circuit are rendered manifest in the receiving telephone by the reproduction of the original Sound in that instrument.